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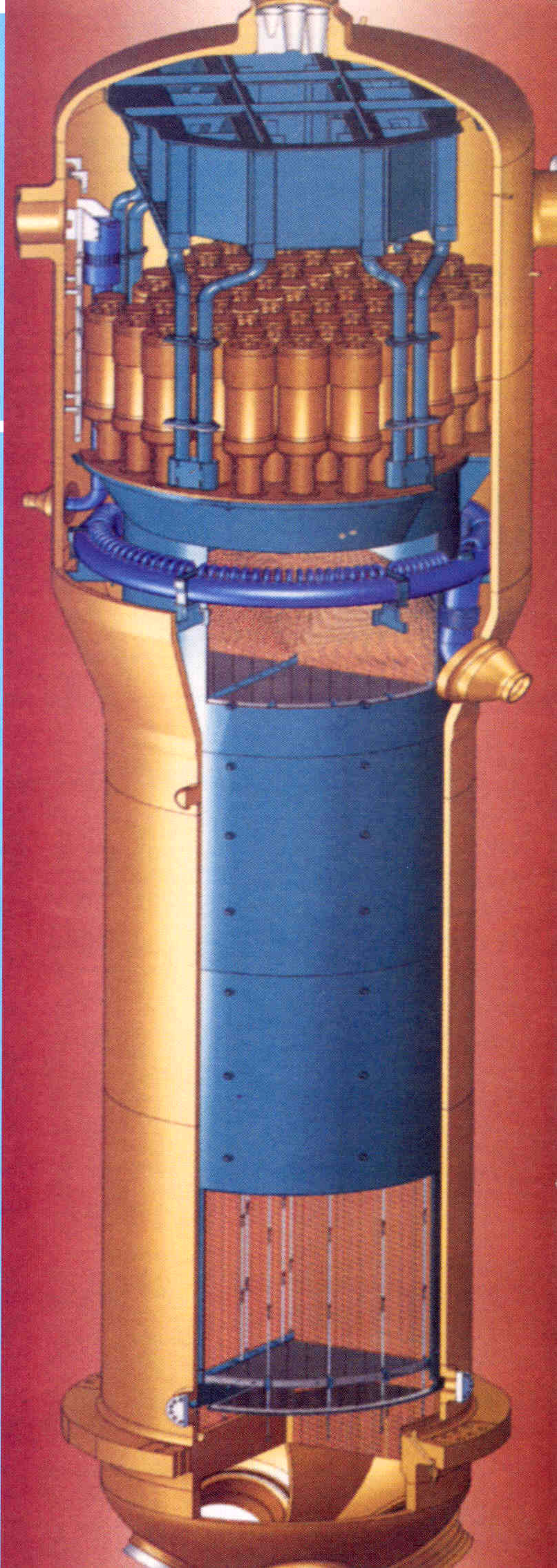

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Uvodnik
Editorial

O projektu posodobitve Jedrske elektrarne Krško
The Krško Nuclear Power Plant Modernisation Project

JE Krško spada – glede na vrsto reaktorja – v tisto skupino jedrskih elektrarn v svetu, pri katerih so uparjalniki nesporno najbolj šibka točka glede dolgoročnega obratovanja. Odločitev za zamenjavo uparjalnikov je primerna najpozneje takrat, ko ni več mogoče načrtovati obratovanja pri polni moči.

Zato smo na podlagi mednarodnih izkušenj, priporočil mednarodnih misij in obratovalnih izkušenj sprejeli odločitev, da se v JE Krško izvede posodobitev. Ta obsega: izdelavo dveh novih uparjalnikov in njuno dobavo, zamenjavo starih uparjalnikov z novima, izdelavo potrebnih varnostnih analiz za zamenjavo in povečanje moči ter vgradnjo popolnega simulatorja. S tem smo se odločili za neposredne varnostne izboljšave, to je sistem za nadzor nezadostnega hlajenja sredice, in posredne, to je vgradnja simulatorja, zamenjava toplotne izolacije uparjalnikov ter odstranitev rezervoarja z natrijevo lužino. Zaradi medsebojne povezanosti podprojektov in njihovega vpliva na varnost in dolgoročnost obratovanja elektrarne smo projekt poimenovali posodobitev JE Krško.

Priprave vsebine, tehničnih značilnosti uparjalnikov, možnih sinergijskih povezav s povečanjem moči, novih postopkov projektiranja, načrtovanja in analiz so se pričele takoj po zamenjavi kondenzatorja v letu 1992.

Cilji posodobitve pa so naslednji:

1. stabilizirati obratovanje do konca dobe trajanja (predvidoma leta 2023),
2. povečati razpoložljivost elektrarne nad 85 odstotkov in predpisati trajanje letnih remontov na približno 35 dni,
3. povečati moč na izhodu za 6 do 7 odstotkov in letno proizvodnjo s 4 TWh na 5 TWh, kar je približno 25-odstotno povečanje,
4. povečati varnost obratovanja z zmanjšanjem tveganja zaradi radioaktivnih izpustov v okolje in zmanjšati število nenačrtovanih zaustavitev,
5. povečati usposobljenost operativnega osebja in zadovoljiti mednarodne standarde,
6. stabilizirati oziroma znižati lastno ceno obratovanja za proizvedeno kilovatno uro.

Krško Nuclear Power Plant (NPP), like a number of other nuclear plants in the world, is equipped with steam generators (SG) with a limited life span: a major obstacle to long-term operation. The decision to replace the existing steam generators is the sensible choice as soon as the full-power operation of the plant can no longer be anticipated.

The decision about long-term plant modernisation is based on the international experience, the recommendations of expert missions and our own operating experience. The project can be divided into four subprojects: manufacture and transport of the steam generators; removal/replacement of the existing steam generators and the necessary constructions; licensing and analyses for the steam generators' replacement project and power increase as well as installation of a plant-specific full-scope simulator. The decision will bring about direct safety improvements, such as an Inadequate-Core-Cooling Monitoring System, as well as indirect ones, like the simulator installation, SG thermal insulation replacement and removal of the NaOH tank. Because of the close relationships between the sub-projects' and their influence on plant safety and long-term operation the project has been called the Krško NPP Modernisation.

The planning, which included the technical characteristics of the SGs, feasible synergy with the power increase, new approaches to designing and analyses started soon after the plant's condenser replacement in 1992.

The specific goals of the Krško NPP Modernisation are:

1. to sustain the operation over the plant's anticipated life until 2023,
2. increase plant availability to a level over 85 per cent and standardise plant refuelling outage duration to approximately 35 days,
3. to uprate the plant's power by 6 - 7 % and to increase total annual power by 25 % production (from 4 TWh to 5 TWh),
4. to increase the overall safety of the plant's operation, minimise the risk of environmental radioactive releases and reduce the number of plant trips and unplanned shut-downs,
5. to improve the qualifications of operation staff and satisfy international standards,
6. to reduce operational costs per kilowatthour of energy produced.

Z načrtovano investicijo bo JE Krško prispevala svoj delež k izvajanju strategije racionalne rabe in oskrbe Slovenije z energijo, ki predvideva nadaljnjo stabilno, varno in zanesljivo obratovanje JE Krško s povečano močjo do konca načrtovane dobe trajanja elektrarne. Sedanja usmeritev porabe električne energije ter odpiranja tržišča z energijo pa takšno opredelitev in investicijo upravičuje.

Martin Novšak
Direktor inženiringa in
ocenjevanja varnosti

The investment in the Krško NPP is a contribution to the Slovenian Energy Consumption and Supply Strategy ensuring continued, stable and reliable power production from the plant, with the added benefit of an increase in the plant's power output during its lifetime. The approach and the investment are justified by both the current consumption of electricity and the demands of the energy market.

Martin Novšak
Director of engineering and
safety evaluation

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Staranje cevi uparjalnikov v Jedrski elektrarni Krško

Aging of Tubes in the Krško Nuclear Power Plant's Steam Generators

Leon Cizelj - Ferdo Androjna

V prispevku predstavljamo domača prizadevanja, ki so omogočila desetletje varnega in zanesljivega obratovanja JE Krško z imensko močjo v bližini projektne meje uparjalnikov – 18 odstotkov začepljenosti cevi. Podajamo pregled stanja in razvoja procesov staranja. Opisujemo kriterije za popravilo cevi, ki določajo sprejemljivo velikost poškodb. Predstavljamo tudi izbrane rezultate varnostnih analiz, ki smo jih izvedli v podporo obratovanju s poškodovanimi cevmi. Povzamemo lahko, da je JE Krško delovala s poškodovanima, a varnima uparjalnikoma.

(Ključne besede: uparjalniki, Inconel 600, varnost, staranje)

The paper reviews the domestic efforts devoted to the safe and reliable operation of the Krško nuclear power plant (NPP) at full power, close to the design limit of the steam generators (18% of plugged tubes) for a full decade. This includes an overview of the recent status and history of the degradation processes, discussion of repair criteria, defining the acceptable size of defects and selected results from safety analyses supporting the operation of degraded steam generator (SG) tubes. It is concluded that Krško NPP operated with degraded, but safe, steam generators.

(Keywords: steam generators, Inconel 600, safety, aging)

0 UVOD

Cevi v uparjalnikih (SG) predstavljajo večino tlačne meje reaktorskega hladiva v tlačnovodnem reaktorju (PWR). Izpostavljene so toplotnim in mehanskim obremenitvam ter agresivnemu delovanju okolja. Cevi iz Inconela 600 (Ni z dodatkom 15% Cr in 8 % Fe) so občutljive za napetostno korozijo v vroči vodi in pari. Razpoke zaradi napetostne korozije so povzročile večino prezgodnjih zamenjav uparjalnikov tlačnovodnih reaktorjev po svetu [1].

Velike poškodbe lahko povzročijo odpoved cevi in zato pomenijo potencialno zmanjšanje razpoložljivosti in varnosti celotne elektrarne. Najpomembnejša načina odpovedi poškodovanih cevi sta:

- porušitev (razpočenje) ene ali več cevi v uparjalniku (SGTR) in
- prekomerno puščanje reaktorskega hladiva na sekundarno stran.

Razpoložljivost in varnost elektrarne vzdržujemo tudi z rednimi pregledi cevi uparjalnikov. Cevi s prevelikimi poškodbami nato popravijo (npr. vstavijo tulce) oz. izločijo iz uporabe (npr. začepijo).

0 INTRODUCTION

The steam generator (SG) tubes represent the majority of the reactor-coolant pressure boundary in a pressurized-water reactor (PWR). They are exposed to thermal and mechanical loads combined with aggressive environmental conditions. The tubes, made of Inconel 600 (Ni with 15% Cr and 8 % Fe), were susceptible to stress corrosion cracking in hot water and steam, the major cause of early retirement of PWR steam generators worldwide [1].

Excessive degradation of tubes might lead to their failure and this leads to a potentially reduced availability and safety of the entire plant. Two potential failure modes of degraded tubing are of particular concern:

- Single or multiple steam generator tube rupture (SGTR),
- Excessive leaking of the reactor coolant to the secondary side.

The availability and safety of the plant is maintained by periodic inspection of SG tubes, which is followed by the repair (e.g., sleeving) or removal from service (e.g., plugging) of the tubes with ex-

Prve cevi so v JE Krško začepili v letu 1985 po komaj treh letih rednega obratovanja elektrarne (od 1982).

JE Krško lahko, v skladu s projektnimi analizami in obratovalnim dovoljenjem, deluje z imensko polno močjo z največ 18% začepljenimi cevmi. Poškodovanost cevi je napredovala dokaj hitro in je dosegla pomemben obseg že med remontom v letu 1990 (sl. 1), ko so se 18-odstotni meji začepljenosti prvič približali. Že takrat je bilo jasno, da zanesljivo in trajno rešitev prinaša le zamenjava uparjalnikov. V obdobju do zamenjave je bilo treba z obsežnimi ukrepi podpreti varno obratovanje s poškodovanimi uparjalniki. Ti ukrepi so:

- spremljanje poškodbe z namenom napovedati kratkoročni in srednjeročni razvoj poškodb in obseg popravil cevi ([3] do [5]);
- primerjalne analize in vpeljava najsodobnejših vzdrževalnih postopkov, dostopnih na trgu, s poudarkom njihovega vpliva na zmanjšanje verjetnosti porušitve cevi in puščanja skozi poškodovane cevi [7];
- ocena tveganj, povezanih s staranjem oz. poškodovanostjo cevi, s sprotnim ocenjevanjem verjetnosti za porušitve cevi in izdatnosti puščanja skozi poškodovane cevi ([7] do [9]).

Glavni namen prispevka je predstavitev domačih prizadevanj, ki so omogočila celo desetletje varnega in zanesljivega delovanja uparjalnikov v bližini njihove projektne meje (18% začepljenost). V prispevku osvetlimo stanje in razvoj procesov staranja (razdelek 1), opišemo kriterije za popravila cevi, ki določajo sprejemljivo velikost poškodb (razdelek 2), in predstavimo izbrane rezultate varnostnih analiz, ki so podprle delovanje s poškodovanimi cevmi (razdelek 3). Povzamemo, da je JE Krško obratovala s poškodovanima, a varnima uparjalnikoma.

1 ZGODOVINA UPARJALNIKOV V KRŠKEM

1.1 Računalniška baza podatkov

JE Krško že od leta 1987 redno pregleduje vse cevi po celotni dolžini s standardnim tipalom s tuljavo (postopek vrtinčnih tokov). V letu 1992 so začeli z rotirajočim tipalom (MRPC) dodatno pregledovati tudi vsa prehodna področja (TTS na sl. 3). V dobrih 14 "dejanskih letih na polni moči (EFPY)" obratovanja uparjalnikov se je nabralo več kot 200.000 zapisov o pregledih cevi. V podporo vzdrževanju uparjalnikov so raziskovalci Odseka za reaktorsko tehniko Instituta "Jožef Stefan" razvili računalniško podprto bazo podatkov [4], ki je bila tudi temelj za vse analize v tem prispevku.

cessive degradation. In the Krško steam generators, the first tubes were plugged in 1985, only three years after the commissioning of the plant in 1982.

The nuclear power plant (NPP) in Krško was designed and licensed to operate at full power with up to 18% of the SG tubes plugged. The degradation developed quickly and gained an increased importance during the 1990 outage (see Figure 1), when the 18% limit had already been approached. It was clear that only the replacement of the steam generators could bring a reliable long-term solution. While waiting for the replacement, comprehensive activities were started to support safe operation with the degraded steam generators:

- Assessment of the degradation aimed at short and medium term predictions of the degradation and repair rates ([3] to [6]);
- Comparative analyses and implementation of the most advanced maintenance options available on the market, with emphasis on the impact on the tube rupture probabilities and the leak rates through degraded tubes [7];
- Assessment of risks associated with tube degradation. In particular, routine estimations of tube rupture probabilities and leak rates through degraded tubes were performed ([7] to [9]).

The main aim of this paper is to review the domestic efforts, which enabled safe and reliable operation of the steam generators at their design limit (18% of plugged tubes) for a full decade. This includes an overview of the recent status and history of the degradation processes (section 1), discussion of the repair criteria defining the acceptable size of defects (section 2) and selected results from safety analyses supporting the operation of degraded SG tubes (section 3). It is concluded that Krško NPP operated with degraded, but safe, steam generators.

1 HISTORY OF THE STEAM GENERATORS AT KRŠKO

1.1 Computerized Data Base

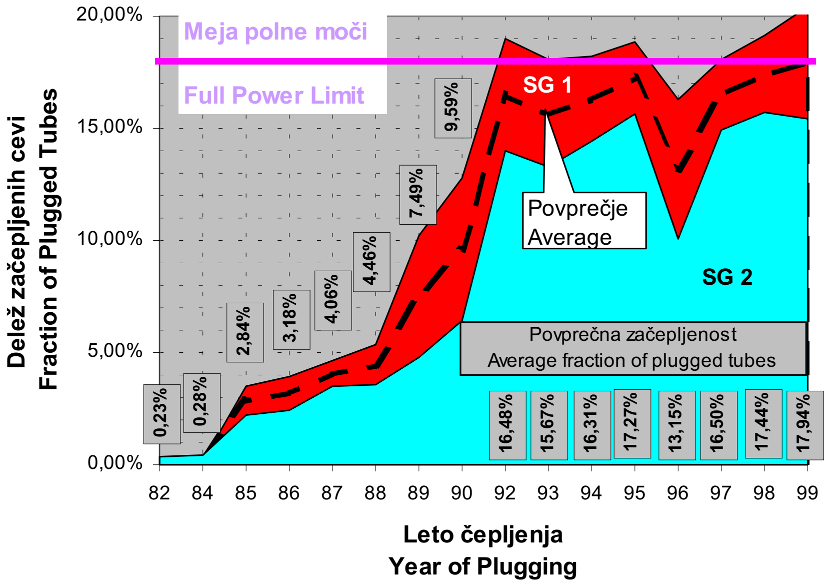
Krško NPP has performed full-length inspection of all tubes by the standard "bobbin coil" (Eddy Current Technique-ECT) method since 1987. In addition, all expansion transitions (TTS, Fig. 3) are inspected by a motorized rotating pancake coil (MRPC) since 1992. More than 200.000 records of inspection results accumulated in nearly 14 effective full-power years (EFPY) of steam generator operation. A computerized database was developed by the Reactor Engineering Division of the "J. Stefan" Institute to support the maintenance of the steam generators [4]. This database was also used for the analyses presented in this paper.

1.2 Pregledi in popravila cevi

Slika 1 prikazuje razvoj popravil cevi v obeh uparjalnikih. Polni črti označujeta deleža začepljenih cevi v SG 1 (zgoraj) in SG 2 (spodaj). Črtkana črta označuje povprečni delež začepljenih cevi v obeh uparjalnikih.

1.2 Inspection and Repair of Tubes

The history of the tube repairs in both steam generators is depicted in Figure 1. The full lines denote the fraction of the tubes plugged in SG 1 (upper) and SG 2 (lower), while the dashed line shows the average fraction of plugged tubes in both steam generators.



Sl. 1. *Potek začepljenosti*

Fig. 1. *History of tube plugging*

V letih 1993 in 1996 opazimo pomembno zmanjšanje števila začepljenih cevi, ki je predvsem posledica vstavljanja tulcev v nekatere ponovno usposobljene-odčepljene-cevi.

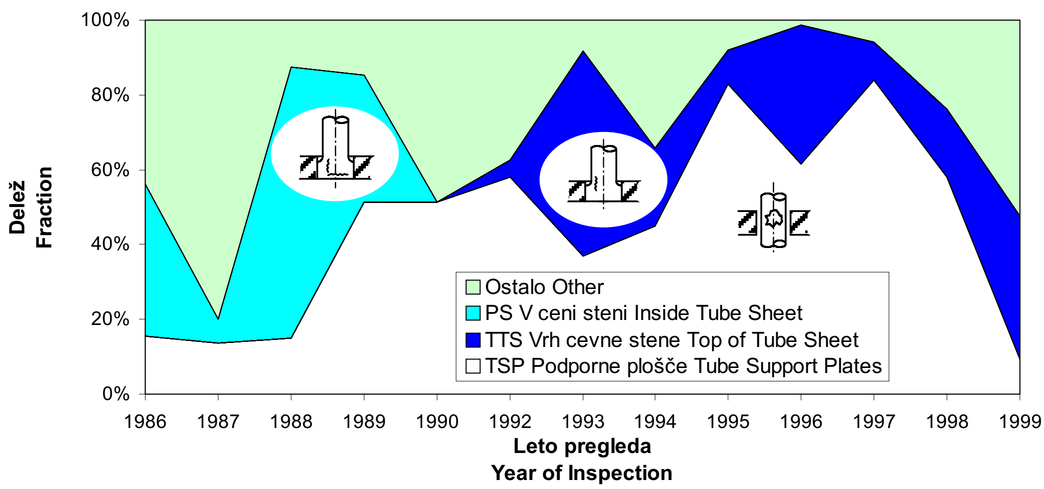
V obdobju po letu 1994 je bilo število na novo začepljenih cevi dokaj stabilno. Izjema je le nenadno povečanje v letu 1997. Pojasnilo je najti v [10].

Slika 2 primerja najpomembnejše vzroke za popravila cevi. Več ko 80% popravil v celotni dobi

A major drop in the number of plugged tubes can be seen in 1993 and 1996. This was a result of the reactivation and sleeving of some of the already plugged tubes.

The repair rates have been relatively stable since 1994, with the exception of in 1997. The explanation for this is attempted elsewhere [10].

The major degradation mechanisms that required the repair of the tubes are compared in Figure 2. More than 80% of tube repairs during the lifetime



Sl. 2. *Glavni vzroki za popravila cevi (SG 1 in SG 2)*

Fig. 2. *Major causes of tube repair (SG 1 and SG 2)*

trajanja uparjalnikov in več kot 90% popravil v zadnjih nekaj remontih pripisujemo le dvema mehanizmoma staranja (sl. 3):

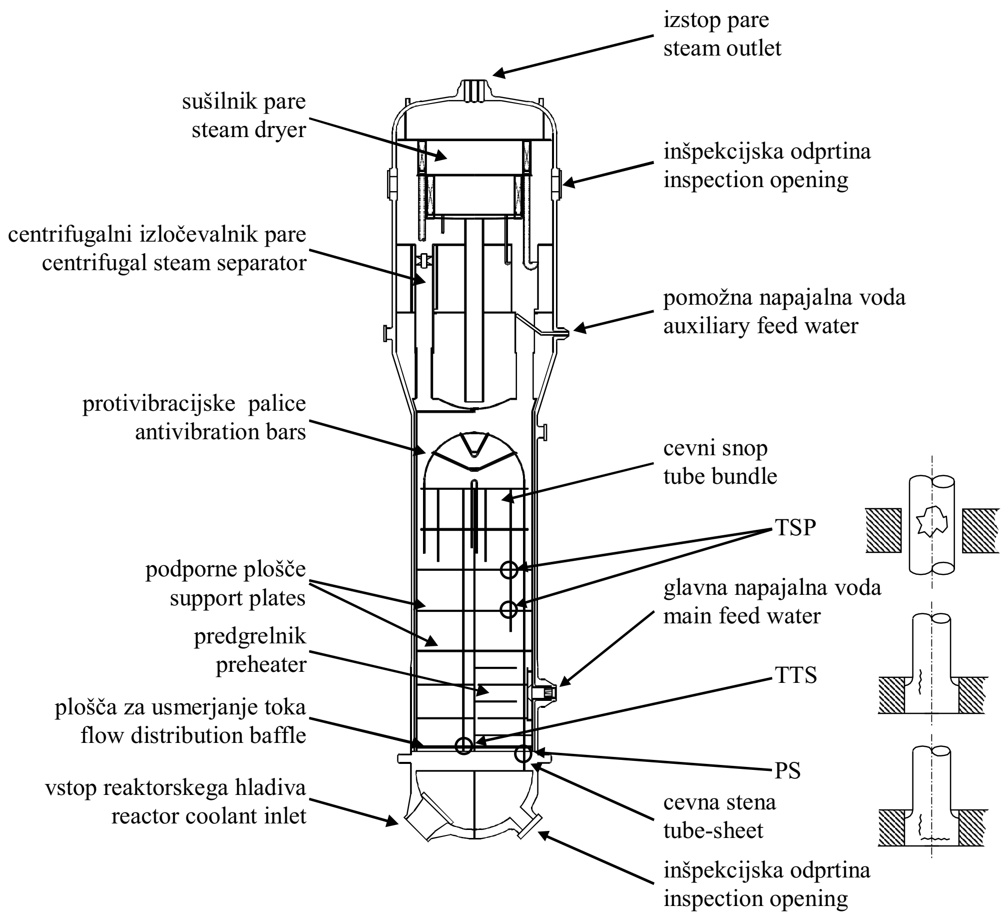
- **TTS:** vzdolžne napetostnokorozijske razpoke v prehodnem področju na vrhu cevne stene (TTS) so povzročile 24% popravil cevi v SG 1 in 17 % v SG 2. Sprejemljiva velikost poškodbe je opisana v razdelku 2.3.
- **TSP:** Napetostno korozijske razpoke na zunanji površini cevi (ODSCC) pod podpornimi ploščami so povzročile 56% popravil v SG 1 in 63 % v SG 2. Sprejemljiva velikost poškodbe je opisana v razdelku 2.4

PS označuje tretji najpomembnejši vzrok za popravila cevi (sl. 2), ki je prevladoval pred letom 1988. To so bile napetostnokorozijske razpoke, ki so v celoti znotraj cevne stene. Varnostne analize, opravljene v letu 1990, so pokazale zelo majhno verjetnost odpovedi cevi zaradi takih poškodb (razdelek 2.2 in [4]).

of the steam generators and more than 90% of repairs during the recent outages are attributed to only two degradation mechanisms (Figure 3):

- **TTS:** axial stress corrosion cracking in the expansion transitions at the top of the tube sheet (TTS) caused 24% and 17% of the repaired tubes in SG 1 and SG 2, respectively. The allowable defect size is described in Section 2.3
- **TSP:** outside diameter stress corrosion cracking (ODSCC) at the tube- support- plate intersections (TSP), caused about 56% and 63% of the repaired tubes in SG 1 and SG 2, respectively. The allowable defect size is described in Section 2.4.

PS denotes the third major cause of tube retirement shown in Figure 2**.** It stands for stress corrosion cracks located entirely within the tube sheet, which dominated tube repairs until 1988. Safety analyses performed in 1990 showed the very low likelihood of tube failure caused by such defects (see Section 2.2 and [4]).



Sl. 3. *Skica uparjalnika z lego najpogostejših vrst poškodb*
Fig. 3. *Sketch of a steam generator with the locations of dominant degradation mechanisms*

Cevi, ki imajo hkrati več poškodb, so k popravilom prispevale približno 10%.

Podrobnejša razprava o tipičnih procesih staranja, značilnih za JE Krško in druge elektrarne po svetu, je v [11].

Tubes with multiple defects represent about 10% of all repairs.

Further discussion of typical degradation mechanisms found at Krško NPP and elsewhere is given in [11].

2 KRITERIJI ZA POPRAVILO CEVI

Pri odločanju o popravilu poškodovane cevi uporabljamo kriterije za popravilo. Tradicionalno uporabljamo splošni kriterij, ki za vse vrste poškodb dovoljuje 40% stanjšanje stene cevi.

V drugi polovici 80. in v 90. letih se je v ceveh uparjalnikov JE Krško in drugih podobnih elektrarnah pojavila napetostna korozija. Ostre in močno razvejane medkristalne razpoke so napredovale skozi steno cevi in včasih povzročile tudi puščanje, še preden so jih odkrili z rednimi pregledi s tradicionalnim tipalom s tuljavo. Sledil je razvoj specializiranih naprav za pregledovanje posameznih vrst poškodb, ki so bile podprte s poškodbam prirejenimi-specifičnimi-kriteriji za popravila cevi. S specifično tehnologijo pregledovanja in analizami porušitev so zmanjšali konzervativnost splošnega kriterija za popravilo cevi.

Osnovni cilj splošnih in specifičnih kriterijev za popravilo je vzdrževanje zanesljivosti in varnosti poškodovanih uparjalnikovih cevi. Kratek opis kriterijev za popravila, ki jih uporablja JE Krško, je v nadaljevanju.

2.1 Splošni kriterij za popravilo

Splošni kriterij za popravilo uparjalnikovih cevi določa najmanjšo sprejemljivo debelino stene cevi [15]. Splošno dovoljeno stanjšanje stene cevi znaša 40%. Splošni kriterij je mogoče uporabiti pri vseh vrstah poškodb (npr., druge na sl. 2), razen tistih, za katere veljajo specifični kriteriji, ki so opisani v nadaljevanju.

2.2 Kriterij P*

Kriterij P* je namenjen cevem, ki so v celotni dolžini uvaljane v cevno steno. Tako sta bila izdelana tudi prvotna uparjalnika za JE Krško. Kriterij dovoljuje delovanje cevem s poškodbami, ki so najmanj za razdaljo P* oddaljene od vrha cevne stene. Vrsta oziroma usmeritev poškodbe pri tem ni pomembna. Kriterij temelji na naslednjem razmisleku: Cevi so trdno vpete v togo cevno steno, ki lahko v celoti prevzame obremenitve cevi tudi pri 360°obodni skozi stenski razpoki. Dolžino P* pa so določili na podlagi zmožnosti sosednjih cevi, da preprečijo izvlek poškodovane cevi iz cevne stene.

Kriterij P* za popravilo cevi je prvi specifični kriterij, uporabljen v JE Krško. Uspešno ga uporabljajo že od leta 1987 (PS na sl. 2).

2.3 Dolžinski kriterij

Dolžinski kriterij je definiran za vzdolžno usmerjene razpoke v prehodnem področju. Prehodno področje je tik nad vrhom cevne stene (TTS), med delom cevi, ki so ga uvaljali - razširili v cevno steno

2 TUBE REPAIR CRITERIA

The decision whether to repair a degraded tube or not is based on repair criteria. Traditionally, a generic repair criterion, allowing for 40% of tube wall thinning, is used for all types of defects.

In the second half of the 80s and in the 90s, stress corrosion cracking appeared in the SG tubes of Krško NPP and in other comparable plants. Sharp and highly branched intergranular cracks grew through the tube wall and sometimes caused leaks before being detected by the regular bobbin coil inspection. Specialized defect-specific inspection equipment was developed, accompanied by defect specific repair criteria. Basically, the conservatism inherent in the generic 40% repair criterion was reduced through defect-specific dedicated inspection technology and failure assessment.

The main goal of generic and defect specific repair criteria is to maintain or improve the reliability and safety of the degraded SG tubes. Brief description of repair criteria applicable for Krško NPP is given below.

2.1 Generic Repair Criterion

The generic repair criterion defines the minimum acceptable wall thickness [15]. The generic allowable defect size is 40% of the wall thickness. The defect depth criterion is applicable to all defects (see other in Figure 2), except for those covered by the defect-specific plugging criteria described below.

2.2 P* Criterion

The P* criterion applies to tubes, hard rolled into the entire depth of the tube sheet, as manufactured in the original Krško steam generators. The criterion allows that tubes with defects located below a certain distance (called P*) from the top of the tube sheet remain in operation without repair, regardless of the defect size or orientation. It makes use of the following consideration: tubes are fixed into the stiff tube sheet, which is able to support the tube even if it contains a 360°circumferential through-wall crack. The P* distance was established by considering the ability of neighboring tubes to prevent the damaged tubes from being pulled out of the tube sheet.

The P* repair criterion was the first defect-specific repair criterion implemented at Krško NPP and has been successfully used since 1987 (see PS in Figure 2).

2.3 Crack-Length Criterion

The crack-length criterion is defined for axially oriented cracks in expansion transitions at the top of the tube sheet. The expansion transitions are located just above the top of the tube sheet (TTS), med izdelavo uparjalnikov, in prostim delom cevi. Razpoke v tem delu cevi so nastale predvsem zaradi dokaj visokih notranjih napetosti [12]. Sprejemljiva velikost poškodbe je definirana kot izmerjena dolžina razpoke. Popraviti je tako treba le cevi z vzdolžno usmerjenimi razpokami, katerih dolžina presega *PL*:

between the portion of the tube which has been expanded into the tube sheet during the manufacture of the steam generators and the free span portion of the tube. The cracks mainly develop here due to the high residual stress [12]. The allowable defect size is defined in terms of the measured crack length. Repair is necessary only for the tubes with axially oriented cracks longer than *PL*:

$$PL = a_c - a_e - a_g \qquad (1),$$

a_c pomeni teoretično kritično dolžino razpoke, a_e največjo pričakovano merilno napako in a_g največji napovedani prirastek razpoke do naslednjega pregleda [3].

Dolžinski kriterij v JE Krško je prirejen po belgijskih izkušnjah [1]. Uporabljajo ga od leta 1992 (TTS na sl. 2). Najdaljša dovoljena izmerjena dolžina vzdolžne razpoke znaša 6 mm (za primerjavo: teoretična kritična dolžina znaša 14,2 mm).

where a_c stands for the theoretical critical crack length, a_e for the maximal expected measurement inaccuracy, and a_g for the maximal predicted crack propagation before the next inspection [3].

The defect length plugging criterion has been used at Krško NPP since 1992 (see TTS in Figure 2) and has basically followed the Belgian approach [1]. The longest allowable axial crack length is 6 mm (for comparison: the theoretical critical crack length is 14.2 mm).

2.4 Kriterij ODSCC

V začetku 90. se je po vsem svetu pojavilo večje število poškodb ODSCC pod podpornimi ploščami (TSP). Zelo zapletena morfologija, tj. močno razvejane mreže razpok, praktično onemogoča analitične napovedi porušitve. Upravljalci elektrarn v ZDA, Franciji in Belgiji so predlagali rešitev, ki temelji na eksperimentalno določeni povezavi med tlakom razpočenja poškodovane cevi in amplitudo signala tipala s tuljavo, ki pomeni merilo velikosti poškodbe (merjeno v voltih - V!). S podobnim postopkom so določili tudi odvisnost med izdatnostjo puščanja skozi poškodbo in amplitudo signala tipala s tuljavo. Lokalne oblasti (v ZDA Nuclear Regulatory Commission – NRC [13]) so tak postopek sprejele. Seveda pa je treba pri uporabi tega kriterija zagotoviti pregledovanje cevi s tehnologijo, ki je enakovredna tehnologiji, uporabljeni pri določanju odvisnosti.

JE Krško kriterija ODSCC ni v celoti vpeljala. Uporabili so le enakovredno tehnologijo pregledovanja cevi, ki omogoča ločitev za varnost pomembnih in manj pomembnih poškodb. Cevi s poškodbami, ki so pomembne za varnost, še vedno popravijo takoj, ko izmerjena globina poškodbe preseže dovoljenih 40% debeline stene cevi (razdelek 2.1).

Posledice takega postopka za varnost elektrarne so opisane v nadaljevanju. Celovita varnostna analiza je opisana v [6].

2.4 ODSCC Criterion

A large number of ODSCC defects under tube support plates (TSP) emerged at the beginning of the 90s on a worldwide scale. The very complex morphology (e.g., the highly branched networks of cracks) of such defects essentially prevents the analytical predictions of failures. A solution proposed by the utilities in the United States, France and Belgium relied on an experimentally determined correlation between the burst pressure of the degraded tube and the bobbin coil signal amplitude, which represents the size of the defect (measured in volts - V!). A similar approach yielded a correlation between the leak rate through the degraded tube and the bobbin coil signal amplitude. Such a criterion was accepted by the local authorities (In the USA by the Nuclear Regulatory Commission (NRC) [13]). Use of non-destructive examination techniques equivalent to those used during the development of correlations is, of course, mandatory.

This methodology was, however, not fully implemented at Krško. The equivalent non-destructive examination techniques were implemented to discriminate between the defects which are either important or less important for safety. The defects important for safety are still repaired if they exceed the allowable tube-wall thickness (see section 2.1).

The safety consequences of such an approach are discussed briefly below. A comprehensive safety analysis is given in [6].

3 VARNOSTNE ANALIZE

Varnostne analize poškodovanih uparjalnikovih cevi so usmerjene v oba načina odpovedi cevi, ki sta opisana v uvodu. Veliko število pogojno ogroženih cevi in uporaba neporušnih

3 SAFETY ANALYSES

Safety analyses of degraded steam-generator tubes are focused on the two failure modes, described in Section 0. The large number of potentially affected tubes and use of non-destructive examinapostopkov za pregledovanje (NDE) stimulirata verjetnostne analize pogojnih odpovedi cevi. Raziskovalci Instituta "Jožef Stefan" smo v zadnjih letih v sodelovanju z JE Krško v ta namen razvili in uspešno uporabili več verjetnostnih metod za ocenjevanje verjetnosti odpovedi uparjalnikovih cevi ([6] do [9]).

Verjetnost za razpočenje in izdatnost puščanja skozi poškodovane cevi smo ocenjevali pri najbolj neugodnem scenariju: pri hipotetični nezgodi z največjo tlačno razliko med primarnim in sekundarnim hladivom, ki se zgodi tik pred pregledom in popravilom cevi. V ta namen ocenimo velikost poškodb ob koncu delovnega obdobja z naključno kombinacijo spodnjih veličin:

- velikosti poškodb ob prejšnjem pregledu;
- negotovosti pregleda z metodo vrtinčnih tokov (ECT)
- večanja poškodb (ocenjeno iz velikosti, izmerjenih v prejšnjih pregledih)

V tem razdelku se posvečamo le napetostnokorozijskim razpokam na zunanji površini cevi (ODSCC) pod podpornimi ploščami (TSP). Poškodbe ODSCC namreč trenutno zahtevajo največ popravil cevi v JE Krško.

3.1 Verjetnost porušitve cevi

Slika 4 prikazuje razvoj verjetnosti porušitve ene izmed cevi uparjalnika v obdobju med 1990 do 1999. Prikazana verjetnost je pogojna in predpostavlja, da se je zgodila malo verjetna hipotetična projektna nezgoda zlom glavnega parnega voda. Za vsakega izmed uparjalnikov obravnavamo dva primera: (1) "vse poškodbe", pri katerem v analizi nismo upoštevali popravljenih cevi in (2) "poškodbe pod 1 V", ki predstavlja popravila cevi v skladu s priporočili [13]. Popravila cevi v JE Krško so bila takšna, da je dejansko stanje med obema krivuljama.

tion (NDE) methods stimulate the probabilistic analysis of potential tube failures. A number of methods aimed at estimating the steam-generator tube failure probabilities have therefore been developed and successfully implemented in recent years in cooperation with the "Jožef Stefan" Institute and Krško NPP (see for example [6] to [9]).

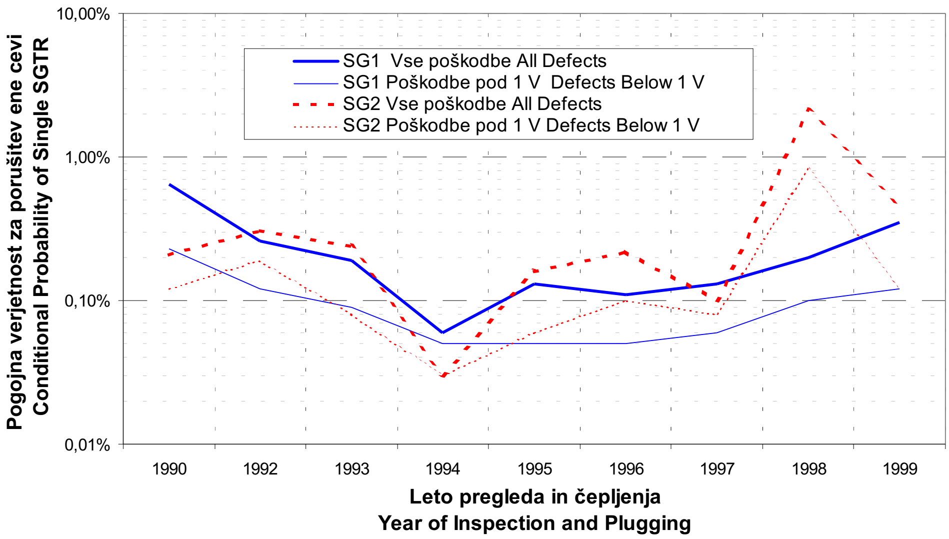
Tube rupture probabilities and leak rates were estimated for a worst-case scenario involving a hypothetical accident with the highest differential pressure across the tube just before the inspection and repair of the tubes. This involves the estimation of the largest defect sizes, estimated by the stochastic combination of the following items:

- Defect sizes at previous inspection;
- Uncertainties of the ECT inspection;
- Defect growth (estimated from the observed defect growth during past inspections).

The particular degradation mechanism addressed in this section is the Outside Diameter Stress Corrosion Cracking (ODSCC) at Tube Support Plates (TSP). ODSCC currently represents the major cause of early tube retirements at Krško.

3.1 Probability of Tube Rupture

Figure 4 depicts the development of a single tube rupture probability in both steam generators during the period 1990 to 1999. The depicted probability is conditional and is assumed to follow a rather unlikely occurrence of a hypothetical design accident Steam Line break. Two cases are considered for each steam generator: (1) "All defects", which means that no credit was taken for tube repair and (2) "defects below 1 V", which represents the tube repair following the recommendations of [13]. The tube repair performed at Krško NPP was between both



Sl. 4. *Pogojna verjetnost porušitve ene cevi med hipotetičnim zlomom parnega voda*
Fig. 4. *Conditional probability of single SGTR given a hypothetical SLB accident*

Zato konzervativno privzamemo krivuljo "vse poškodbe".

Slika 4 kaže dve različni usmeritvi. Za obdobje med 1995 in 1999 je značilno naraščanje verjetnosti porušitve ene cevi, kar je v skladu z naraščajočim pojavom poškodb ODSCC. Po drugi strani kaže obdobje med 1990 in 1994 zmanjševanje verjetnosti porušitve ene cevi. Glavni razlog za to je sprememba tehnologije za neporušne preglede: nova, s priporočili [13] usklajena tehnologija pregledovanja cevi je bila prvič uporabljena v letu 1994. Dosledni rezultati so tako na voljo le za obdobje med 1995 in 1999.

Povprečna pogojna verjetnost porušitve ene cevi v obeh uparjalnikih ("vse poškodbe") je bila v opazovanem obdobju daleč pod mejo 1%, pri kateri je v skladu s priporočili NRC GL-95-05 [13] stanje treba prijaviti upravnemu organu. Verjetnost za porušitev več ko ene cevi je bila v vseh obravnavanih primerih za najmanj dva velikostna razreda manjša. Povzamemo torej lahko, da je JE Krško delovala s poškodovanima, a varnima uparjalnikoma.

Podrobnejši pregled uporabljenih metod in vhodnih podatkov je v [6] in [7].

3.2 Puščanje skozi poškodovane cevi

Slika 5 prikazuje razvoj ocenjene izdatnosti puščanja v obdobju med 1990 do 1999. Prikazana izdatnost puščanja je pogojna in predpostavlja, da se je zgodila malo verjetna hipotetična projektna nezgoda zlom glavnega parnega voda. Za vsakega izmed uparjalnikov obravnavamo dva primera: (1) "vse poškodbe", pri katerem v analizi nismo upoštevali popravljenih cevi in (2) "poškodbe pod 1 V", ki predstavlja popravila cevi v skladu s priporočili

curves. In further discussion it is therefore conservative to rely on the "All defects" curve.

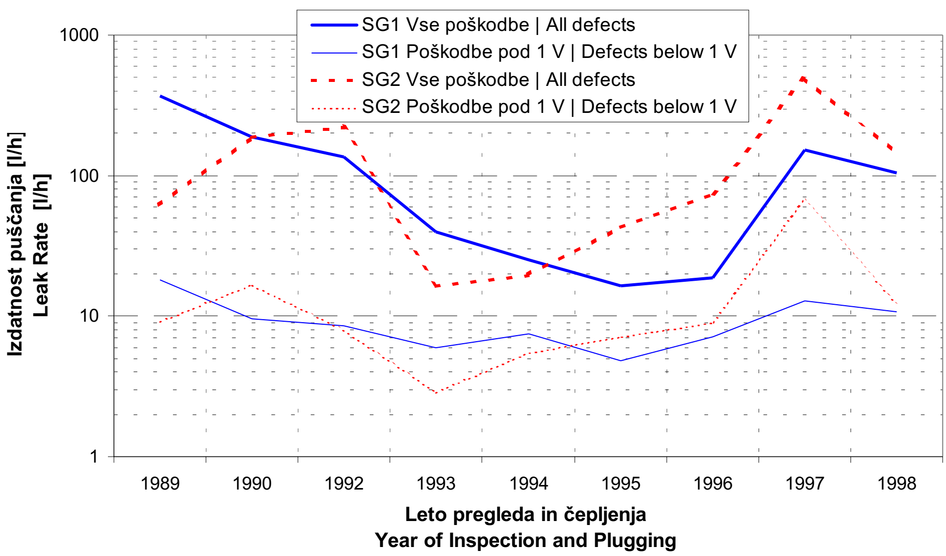
Two different trends may be observed in Figure 4. In the period 1995 to 1999, the probability of tube rupture decreases, which is consistent with the growing population of ODSCC defects. On the other hand, the period 1990 to 1994 exhibits a decreasing probability of tube rupture. The main reason for this is a change in the non-destructive examination technology: the first implementation of [13] compliant NDE methods dates back to 1994. Consistent results are therefore obtained only for the period 1995-1999.

The average conditional single-tube-rupture probability of both steam generators ("All defects") was well below the reportability threshold of 1% which is foreseen in NRC GL-95-05 [13] during the period depicted in Figure 4. The probability of multiple tube rupture was at least two orders of magnitude lower in all the analysed cases. It may therefore be concluded that Krško NPP operated with degraded, but safe, steam generators.

Details about the methods and input data can be found in [6] and [7].

3.2 Leaking of Reactor Coolant Through Degraded Tubes

Figure 5 depicts the development of estimated accidental leak rates in both steam generators in the period 1989 to 1998. The depicted leak rates are conditional and are assumed to follow a rather unlikely occurrence of a hypothetical design accident Steam Line break. Two cases are considered for each steam generator: (1) "All defects", which means that no credit was taken for the tube repair and (2) "defects below 1 V", which represent the tube repair



Sl. 5. *Ocenjene izdatnosti puščanja ob hipotetični nezgodi zlom parnega voda*
Fig. 5. *Estimated leak rates given a hypothetical SLB accident*

[13]. Popravila cevi v JE Krško so bila takšna, da je dejansko stanje med obema krivuljama. Zato lahko konzervativno privzamemo krivuljo "Vse poškodbe".

Slika 5 prikazuje dve različni usmeritvi. Za obdobje med 1995 in 1999 je značilno rahlo naraščanje izdatnosti puščanja skozi poškodovane cevi , kar je v skladu z naraščajočim pojavljanjem poškodb. Obdobje med 1990 in 1994 pa kaže na rahlo zmanjševanje izdatnosti puščanja. Glavni razlog za to je sprememba tehnologije za neporušne preglede: nova, s priporočili [13] usklajena tehnologija pregledov je bila prvič uporabljena v letu 1994. Dosledni rezultati so tako na voljo le za obdobje med 1995 in 1999.

Konzervativno ocenjene največje izdatnosti puščanja v obeh uparjalnikih so v velikostnem razredu 0,2 m^3/h v SG 1in 0,5 m^3/h v SG 2 (1997). To je daleč pod priporočeno največjo izdatnostjo puščanja med projektno hipotetično nezgodo zloma glavnega parovoda 19 m^3/h [14], ki zagotavlja še dovoljene obremenitve okolja. Za primerjavo povejmo, da sme JE Krško v skladu z veljavnim obratovalnim dovoljenjem obratovati z izdatnostjo puščanja največ 40 l/h na uparjalnik. Sklepamo torej lahko, da je JE Krško delovala s poškodovanima, a varnima uparjalnikoma.

Podrobnejši pregled uporabljenih metod in vhodnih podatkov je v [6] in [8].

following the recommendations of f13]. The tube repair performed at Krško NPP was between both curves. It is therefore conservative to rely on the "All defects"curve.

Two different trends may be observed in Figure 5. In the period 1995 to 1999, the leak rate through both steam generators was increasing, which is consistent with the growing population of ODSCC defects. On the other hand, the period 1990 to 1994 exhibits a decreasing leak rate. The main reason for this is a change of the non-destructive examination technology: the first implementation of [13] compliant NDE methods dates back to 1994. Consistent results are therefore obtained only for the period 1995-1999.

The conservatively predicted highest accidental leak rates for both steam generators are in the order of 0.2 m^3/h in SG 1 and 0.5 m^3/h in SG 2 for 1997. This is well below the recommended maximum leak rate of 19 m^3/h [14], allowed during a hypothetical SLB. For comparison, the Krško NPP is licensed to operate normally with a leakage of up to 40 l/h through any of the steam generators. It may therefore, again be concluded, that Krško NPP operated with degraded, but safe, steam generators.

Details about the methods and input data can be found in [6] and [8].

4 SKLEPI

V prispevku so predstavljena najpomembnejša domača prizadevanja za zagotavljanje varnega in zanesljivega delovanja uparjalnikov v JE Krško. Še posebej smo se posvetili zadnjemu desetletju obratovanja elektrarne. Za to obdobje je značilno, da sta uparjalnika obratovala v bližini njune projektne meje 18% začepljenosti, in je postalo jasno, da lahko le zamenjava uparjalnikov prinese trajno in zanesljivo rešitev.

Pregledali smo trenutno stanje in razvoj procesov staranja, opisali smo kriterije za popravila cevi, ki določajo sprejemljivo velikost poškodb, in predstavili izbrane rezultate varnostnih analiz, ki so podprle delovanje s poškodovanimi cevmi.

Povzeli smo, da je JE Krško z veliko pomočjo domačega znanja delovala s poškodovanima, a varnima uparjalnikoma.

4 CONCLUSIONS

The main domestic efforts devoted to the safe and reliable operation of the Krško steam generators are reviewed in this paper. The main focus is given to the last decade of plant operation. In the beginning of this period, the steam generators approached the limit of 18% plugged tubes and it became clear that only the replacement of the steam generators could bring a reliable long-term solution.

The main topics include an the overview of the recent status and the history of degradation processes, discussion of repair criteria defining the acceptable size of defects and selected results from safety analyses supporting the operation of degraded SG tubes.

It is concluded that Krško NPP's operation with degraded, but safe, steam generators, was to a significant extent, based on domestic knowledge.

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Pomen varjenja pri izdelavi uparjalnikov za Jedrsko elektrarno Krško

The Role of Welding in the Manufacture of the Steam Generators for the Krško Nuclear Power Plant

Janez Tušek - Andrej Lešnjak - Borut Zorc - Jože Zorko - Franc Krošelj

V članku je opisana tehnologija zvarjanja in navarjanja, uporabljena pri izdelavi uparjalnikov za Jedrsko elektrarno Krško. Predstavljeni so najpomembnejši zvarni spoji in najpomembnejši navari. Vseh zvarnih spojev in varov pa ni bilo mogoče predstaviti, saj jih je samo v enem uparjalniku okrog 60 000. V prvem delu članka je opisano navarjanje notranje površine primarne glave uparjalnika. Uporabljeno je bilo navarjanje s tračno elektrodo pod praškom. V drugem delu je predstavljena izdelava zvarnih spojev med cevjo in cevno steno. Vseh 5428 cevi je spojenih s cevno steno na dveh koncih z obločnim varjenjem TIG ter hidravlično ekspanzijo in mehanskim uvaljanjem. Varjenje predelne stene na primarno glavo in cevno steno je opisano v tretjem delu članka. Z makro obrusom sta predstavljena oba zvarna spoja predelne stene s cevno steno in s primarno glavo. V zadnjem delu pa najdemo opis varjenja krožnih varov na plašču uparjalnika. Tu sta bila uporabljena dva različna obločna postopka varjenja. Koren vara je bil varjen z oplaščeno elektrodo, preostali vari pa avtomatsko pod praškom. Na koncu članka so podani sklepi, v katerih je navedeno, da so bile tehnologije varjenja pravilno izbrane in med izvajanjem zelo dobro nadzorovane, kar je zagotovilo, da je uparjalnik izdelan zelo kakovostno.

(Ključne besede: tehnika jedrska, uparjalniki, navarjanje s praški, varjenje TIG)

This paper describes welding and cladding technologies used in the manufacture of the steam generators for the Krško Nuclear Power Plant. The most important welded joints and claddings are treated, however, all the welded joints and claddings could not be treated because there are around 60.000 in each steam generator. First, cladding of the inner surface of the primary head of the steam generator is described. Submerged-arc cladding with a strip electrode was used for this purpose. Then the production of the welded joints between a tube and a tube sheet is described. All 5428 tubes were joined to the tube sheet, at each end, by TIG welding, preceded by mechanical rolling-in and hydraulic expansion. Welding of a partition plate to the primary head and to the tube sheet is described in the third part of the paper. Both welded joints, i.e. the one between the partition plate and the tube sheet and the one between the partition plate and the primary head, are shown as macro sections. Finally, welding of circumferential welds at the steam-generator shell is described. Two different arc welding processes were used for the purpose. The weld root was manually arc welded with a covered electrode while other welds were automatically submerged-arc welded. In the conclusions, it is stated that the welding technologies used were selected properly and well controlled during execution, which ensured the quality of the steam generator.

(Keywords: nuclear power engineering, steam generators, submerged-arc cladding, TIG welding)

0 UVOD

Kolikšen pomen ima končni izdelek, kakšna je njegova cena, kakšna sta obseg in kakovost nadzora ter preverjanja med njegovo izdelavo je v največji meri odvisno od tveganja pri njegovi uporabi.

Glede na prej omenjene kriterije je uparjalnik za jedrsko elektrarno prav gotovo

0 INTRODUCTION

The importance of the final product, its price, the extent and quality of supervision and control during its production, depend mainly on the risks involved in its exploitation.

It is clear from the above, that the way in which a steam generator is made exceptionally imizjemnega pomena, saj mora biti zanesljivost njegovega delovanja na najvišji mogoči ravni.

Uparjalnik je tlačna posoda, v kateri se ločeno pretakata dve tekočini pod visokim tlakom in pri visoki temperaturi. Na primarni strani se pretaka reaktorsko hladivo, na sekundarni strani pa voda, ki se upari in nato uporabi za pogon turbine.

Večina elementov uparjalnika (glede na celotno maso) je izdelana iz jekla za poboljšanje. Nekateri od teh elementov, predvsem tisti na primarni strani, so na notranji strani navarjeni z močno legiranim nerjavnim jeklom ali nikljevimi zlitinami (teh površin je v vsakem uparjalniku približno 35 m^2). Cevi, po katerih se pretaka reaktorsko hladivo, pa so izdelane iz zlitine niklja, kroma in železa s poslovno oznako inconel.

Posamezni deli uparjalnika so bili med seboj zvarjeni po talilnih postopkih (pod praškom, TIG), drugi z elektrouporovnim točkovnim varjenjem in tretji z mehansko silo v hladnem. Zvarne spoje sestavljajo različne vrste materialov različnih debelin in oblik. Prav zaradi uporabe različnih materialov so bili postopki varjenja izjemno zahtevni, pred varjenjem, med njim in po njem pa je bilo treba izvajati še dodatne ukrepe.

1 NAVARJANJE PRIMARNE GLAVE UPARJALNIKA

Primarna glava uparjalnika je eden od pomembnejših elementov, ki ga na vroči in hladni del loči predelna stena. V vroči del priteka reaktorsko hladivo, ki se nato pretaka prek cevnega sistema, v katerem odda toploto, v drugi, hladni del in nato nazaj v reaktor.

Na sliki 1 je shematsko prikazana primarna glava uparjalnika z označenimi navari. Ta je bila v grobem izdelana s kovanjem v vročem v temperaturnem območju od 800 do 300 °C. Celotna površina notranjosti glave je bila navarjena. Zaradi zapletenih oblik je bilo navarjanje izvedeno po več različnih postopkih. Največjo notranjo površino, ki ima obliko polkrogle z oznako 002 – slika 1, je bilo treba navariti s tračno elektrodo dimenzije 60 × 0,5 mm iz avstenitnega nerjavnega jekla. Navarjanje pod praškom je bilo treba izvesti v najmanj dveh slojih z uporabo dveh različnih dodajnih materialov. Debelina vseh slojev je morala po varjenju in brušenju navarjene površine znašati od 7,5 do 9,5 mm. Brušenje je moralo biti izvedeno, da smo dobili gladko površino. Primarna glava ima štiri odprtine. Dve (manjšega premera) sta namenjeni za vstop in nadzor ter popravilo notranjosti primarne glave, zato se tudi imenujeta odprtini za ljudi. Drugi dve odprtini pa sta priključka za dovod in odvod primarnega medija, to je pregrete vode pri visoki temperaturi in visokem tlaku. Notranjost teh štirih odprtin z oznakama 004 in 006 (sl. 1) je bila navarjena s tračno elektrodo enake sestave, kakršno je imela elektroda, uporabljena

portant, since its operational reliability has to be at the highest possible level.

A steam generator is a pressure vessel in which two pressurised media at an elevated temperature flow separately. On the primary side there is a reactor coolant, and on the secondary side there is water, which evaporates and is used for the turbine drive.

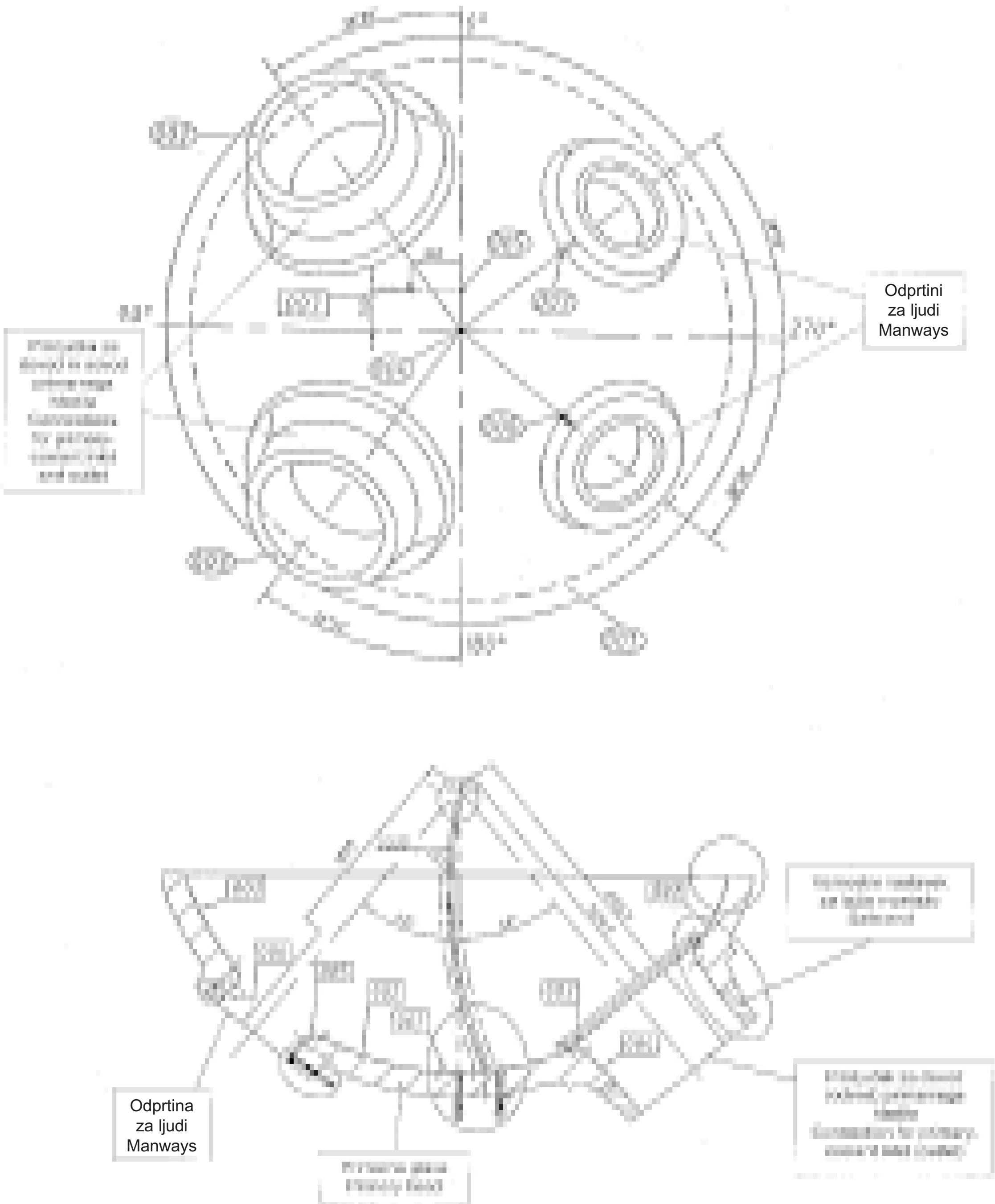
The majority of steam-generator elements, with regard to the whole mass, are made of heat-treated steel. The inside wall of some of the elements, particularly those on the primary side, are surfaced with high-alloy stainless steel or nickel alloys (an area amounting to around 35 m^2 in each steam generator). The tubes in which the coolant flows are made of a nickel-chrome-iron alloy, commercially designated as Inconel.

The individual steam-generator elements were fusion welded, i.e., submerged-arc welded, TIG welded, while others were resistance-spot welded or cold-pressure welded. These welded joints are made of different materials, and are of different sizes and shapes. Owing to the variety of materials, the welding procedures were extremely exacting and additional measures were required before, during and after welding.

1 CLADDING OF THE PRIMARY STEAM-GENERATOR HEAD

The primary steam-generator head is one of the most important elements, it is separated into a cold part and a hot part by a partition plate. The reactor coolant passes first into the hot part, after which it passes through a system of tubes where heat is discharged, and then into the second, cold, part and finally back into the reactor.

The primary steam-generation head, with the claddings indicated, is shown schematically in Fig. 1. It was roughly hot forged in the temperature range from 800 to 300 °C. The entire internal surface of the head was surfaced. Because of the intricate shapes, cladding was carried out using different procedures. The largest internal surface, having the shape of a hemisphere and designated with number 002 (Fig. 1), had to be surfaced with an austenitic stainless-steel strip electrode of 60 x 0.5 mm. Submerged-arc cladding was carried out in at least two layers using two different filler materials. After welding and grinding the thickness of all the layers should be 7.5 to 9.5 mm. Grinding should be used to obtain a smooth surface. The primary head has four openings. Two of them, the ones with the smaller diameter, are designed for entrance and control as well as repairs to the inside of the primary head, because of this, they are called manways. The other two openings are connections for supply and discharge of the primary coolant, i.e. pressurised hot water. The inside of the four openings (004 and 006 - Fig. 1) was surfaced with a strip electrode having the same composition as the elec-



Sl. 1. *Shematski prikaz primarne glave uparjalnika*
Fig. 1. *Schematic presentation of the primary steam-generator head*

za notranje navarjane površine (oznaka 002), in s prerezom 30 × 0,5 mm. Druge navare, ki so označeni na sliki 1, je bilo treba navariti ročno obločno z oplaščenimi elektrodami. Tudi te površine so bile navarjene v več slojih z oplaščenimi elektrodami različnih kemičnih lastnosti oziroma sestave.

1.1 Uporabljeni materiali

Kakor smo že omenili, je celoten uparjalnik izdelan iz različnih vrst materialov. Primarna glava

trode used for cladding the surface designated “002” and was 30 x 0.5 mm in cross-section. The other claddings indicated in Fig. 1 had to be manually arc welded with covered electrodes. Also, these surfaces were welded in several layers with covered electrodes having different chemical properties, i.e. compositions.

1.1 Materials used

The steam generator is constructed of different materials. The primary head is made of a low-je izdelana iz malo legiranega jekla za poboljšanje s kemično sestavo, navedeno v preglednici 1, in oznako SA 508 C13A.

alloy heat-treatment steel SA 508 C13A with a chemical composition given in Table 1.

Preglednica 1. *Kemična sestava osnovnega materiala za primarno glavo uparjalnika in dveh dodajnih materialov v obliki tračnih elektrod za navarjanje plasti v več slojih z oznako 002 (Fig. 1) in sestava dodajnega materiala za TIG varjenje cevi na cevno steno*

Table 1. *Chemical composition of the parent metal for the primary steam-generator head, of two filler materials, i.e. two strip electrodes, for cladding of several layers designated with number 002 (Fig. 1), and of the filler material for TIG welding of tubes to the tube sheet*

	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	V %	Nb %	Co %	Cu %
Osnovni material Parent metal	≤0,25	0,15-0,40	1,20-0,40	0,025	0,025	≤0,25	0,45-0,60	0,40-1,00	≤0,45	/	/	/
Dodajni material za prvi sloj 1st layer filler material	≤0,03	0,15-0,50	1,0-2,5	0,015	0,008	23,5-24,5	<0,30	12,0-13,0	/	0,6-1,0	≤0,05	≤0,20
Dodajni material za drugi sloj 2nd layer filler material	≤0,04	0,30-0,65	1,0-2,5	0,03	0,008	19,5-21,5	≤0,75	9,0-11,0	/	/	≤0,05	≤0,75
Dodajni material za TIG varjenje TIG welding filler material	0,05	0,08	2,9	0,005	0,001	20,25	/	71,5	/	/	0,05	0,22

S toplotnim poboljšanjem pri izdelavi primarne glave so se mehanske lastnosti osnovnega materiala močno izboljšale. Te lastnosti je bilo treba obdržati tudi po navarjanju s tračno elektrodo pod praškom. Najpomembnejši ukrep je bil tako predgrevanje varjenca pred varjenjem in vzdrževanje primerne temperature med varjenjem. Navar je bil izdelan iz več slojev nerjavnega avstenitnega jekla različne kemične sestave. Za prvi sloj je bila uporabljena tračna elektroda, s splošno trgovsko oznako CrNi 24.13 L Nb in po klasifikaciji ASME SFA 5.9 ER 309 L (Nb), proizvajalca SANDVIK, Švedska. Kemična sestava tračne elektrode za navarjanje prvega sloja je navedena v preglednici l.

Za drugi in tretji sloj je bila uporabljena tračna elektroda iz nekoliko manj legiranega avstenitnega nerjavnega jekla. Njena splošna oznaka je CrNi 19.9 L Nb in po klasifikaciji ASME SFA-5.9 ER 347. Podrobna kemična sestava je prav tako navedena v preglednici l.

S poskusi je bilo ugotovljeno, da je v obeh navarih, ki nastaneta iz zgoraj navedenih tračnih elektrod, 9 odstotkov delta ferita.

Evropski standard za dodajni material za navarjanje v obliki tračne elektrode še ne obstaja.

Strukture osnovnih in dodajnih materialov lahko določimo v Schaefflerjevem diagramu (sl. 2) z uporabo enačb:

Quenching and tempering used in the manufacture of the primary head considerably improved the mechanical properties of the parent metal. These properties should not be lost after submerged-arc cladding with the strip electrode. The most important measure was, therefore, preheating of the workpiece prior to welding and maintenance of a suitable temperature during the welding. The cladding consists of several layers of austenitic stainless steel having different chemical compositions. For the first layer the strip electrode with the trade mark CrNi 24.13 L Nb and SFA 5.9 ER 309 L (Nb), according to ASME classification, produced by SANDVIK, Sweden, was used. The chemical composition of the strip electrode for cladding of the first layer is given in Table 1.

For the second and third layers the strip electrode of a less-alloyed austenitic stainless steel was used. Its general designation is CrNi 19.9 L Nb and SFA-5.9. ER 347 according to ASME. Its chemical composition is also given in Table 1.

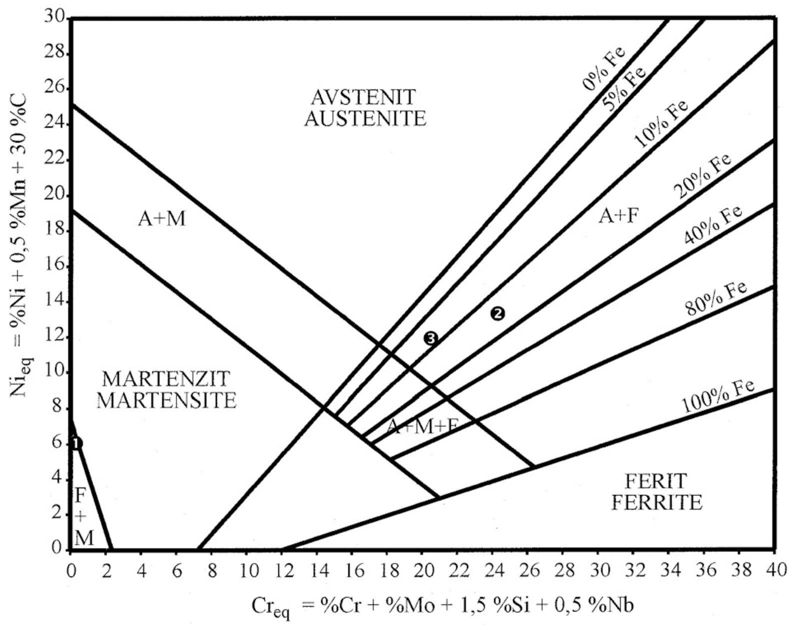
The experiments showed that both claddings made with the strip electrodes contain 9 % of delta ferrite.

There is currently no European standard for a strip-electrode filler material for cladding.

The structures of the parent metals and the filler materials can be determined in the Schaeffler diagram (Fig. 2) by means of the following equations:

$$Cr_{ekv} = \% Cr + \% Mo + 1,5 \% Si + 0,5 \% Nb \quad (1),$$

$$Ni_{ekv} = 30 \% C + \% Ni + 0,5 \% Mn \quad (2).$$



Sl. 2. *Schaefflerjev diagram z oznakami struktur osnovnega materiala in obeh dodajnih materialov za prvi in drugi sloj navara na notranji površini primarne glave*

Fig. 2. *Schaeffler diagram with indications of structures of the parent metal and the two filler materials used for the first and second layers of the cladding at the internal surface of the primary head*

1.2 Opis praktičnega navarjanja s tračno elektrodo pod praškom

Varjenje s tračno oblikovano elektrodo je znano že skoraj osemdeset let. Leta 1920 je bil namreč v Nemčiji podeljen patent št. 37008 92 za tračno oblikovan dodajni material. V praksi se postopek največkrat uporablja za navarjanje s tračno elektrodo iz avstenitnega nerjavnega jekla, kakor je to bilo tudi pri izdelavi primarne glave uparjalnikov za jedrsko elektrarno ([1] do [4]).

Dodajni material lahko uporabljamo v obliki ravnega ali pa tudi polkrožnega traku. Lahko se navarja z eno ali pa z dvema elektrodama hkrati [5]. Prečni prerezi trakov znašajo od 20 × 0,2 mm do 180 × 0,5 mm [6]. Na sliki 3 sta prikazana dva trakova 60 × 0,5 mm po ustavitvi varjenja. Takšen trak je bil uporabljen za navarjanje notranje površine primarne glave. Na spodnji strani obeh trakov je gorel en ali pa hkrati dva ali celo več oblokov. Ti so talili trak, del osnovnega materiala in del praška. Iz oblike spodnjega roba traku, kjer je gorel oblok in se je talil dodajni material, lahko pridemo do nekaterih ugotovitev.

Zanesljivo lahko trdimo, da sta v točki 1 in 2 (sl. 3) tik pred ustavitvijo procesa gorela obloka. Na levem traku pa je nazadnje oblok gorel v točkah 3, 4 in 5. V točkah l in 2 se je oblikovala kapljica, v točkah 6 in 7 pa se je kapljica ravnokar odtrgala. V

1.2 Practical trials of submerged-arc cladding with a strip electrode

Welding with a strip electrode has been known for almost eighty years. It was in 1920 that patent no. 37008 92 for a strip-shaped filler material was granted. In practice this procedure is mostly used for cladding with an austenitic stainless-steel strip electrode as was the case for the fabrication of the primary steam-generator head for a nuclear power station ([1] to [4]).

The filler material may be in the shape of a straight or semicircular strip. Cladding may be carried out with a single electrode or two electrodes simultaneously [5]. Cross-sections of the strips vary between 20 x 0.2 mm and 180 x 0.5 mm [6]. Fig. 3 shows two strips of 60 x 0.5 mm after welding. Such a strip was used for cladding the internal surface of the primary head. At the lower side of each strip one, two or even more arcs were burning at the same time. They were melting the strip, a part of the parent metal and a part of the flux. The shape of the lower strip edge, where the arc was burning and the filler material was melting, permitted us to draw a few conclusions.

It may be affirmed with certainty that at points 1 and 2 (Fig. 3) two arcs were burning immediately before the process stopped. With the left strip, the arc was burning last at points 3, 4, and 5. At points obeh primerih sta se odtrgali zelo veliki kapljici. Prav gotovo je bil premer kapljice od dva- do trikrat večji, kakor je debelina traku. Zaradi prehoda raztaljenih kapljic iz traku se dolžina oblokov stalno spreminja in oblok ali obloki se med varjenjem stalno selijo po vsej njegovi širini. Po grobi oceni se ta dolžina oblokov spreminja od nekaj milimetrov pa celo do pet milimetrov.

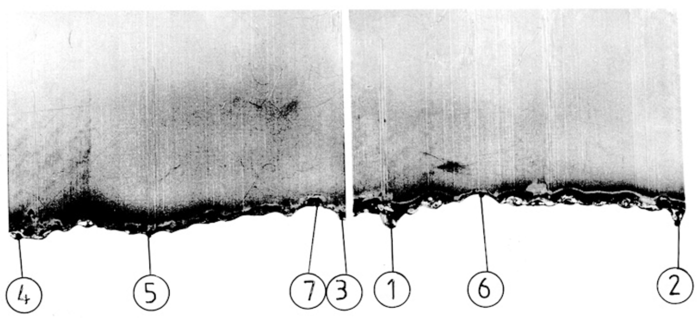
Na sliki 4 sta prikazana dva dela traku dimenzije 30 × 0,5 mm, ki sta se uporabljala za navarjanje notranjosti vseh štirih odprtin primarne glave z oznakama 004 in 006 (sl. 1).

Tudi iz teh posnetkov (sl. 4) lahko ugotovimo, da je hkrati gorelo več oblokov in da sta se sočasno lahko odtalili dve ali celo več kapljic. Na koncu traku (sl. 4 - desno) vidimo tri različno velike kapljice. Iz tega lahko sklepamo, da so tik pred ustavitvijo varjenja istočasno goreli trije obloki. Na sredini drugega traku (sl. 4 - levo) pa je nastala samo ena kapljica. Iz oblike robu pa lahko ocenimo, da se je po celotni širini traku naredilo od 5 do 7 kapljic. Kapljice so bile zaradi površinske napetosti okrogle oblike s premerom od 1 do 2,5 mm. Po klasifikaciji IIW (Mednarodni inštitut za varilstvo) lahko uvrstimo ta način

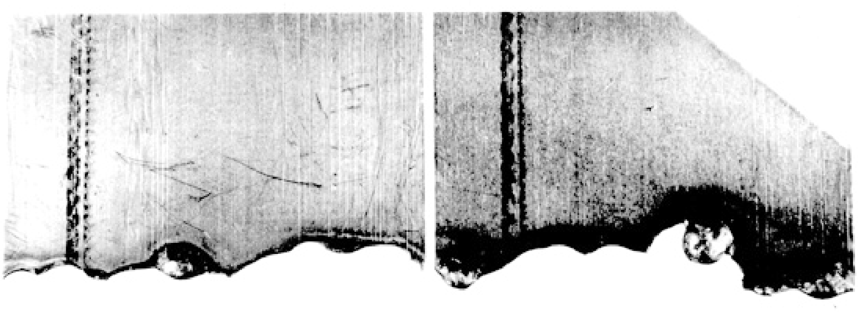
1 and 2 a droplet was formed, and at points 6 and 7 it had just detached. In both cases rather large droplets detached. The droplet diameter was at least two to three times the strip thickness. Because of the detachment of the molten droplets from the strip, the arc lengths were constantly changing, and an arc or arcs were constantly moving across its width during welding. According to a rough estimation, the arc lengths were constantly varying between a few millimetres and five millimetres.

Fig. 4 shows two parts of a strip of 30 x 0.5 mm which was used for cladding the inside of the four openings of the primary head, designated with numbers 004 and 006 (Fig. 1).

Also these photos indicate that several arcs were burning at the same time and that two or more droplets could be melted off. At the strip edge (Fig. 4, right) three droplets of different sizes can be seen. It may be concluded that immediately before the end of welding three arcs had been burning simultaneously. In the middle of the second strip (Fig. 4, left) a single droplet formed. The edge shape allows us to conclude that 5 to 7 droplets were formed along the total strip width. Because of surface tension, the droplets were round with a diameter varying from 1 to 2.5 mm. According to the IIW (International In-



Sl. 3. *Konca traku iz nerjavnega jekla (60 x 0,5 mm) za navarjanje pod praškom s spodnjima robovoma, kjer so goreli en, dva ali več oblokov, ki so se gibali po traku prečno sem in tja in talili dodajni material*
Fig. 3. *Two parts of a stainless steel strip (60 x 0.5 mm) for submerged-arc cladding showing the lower edges at which one, two or more arcs moving across the strip to and fro and melting the filler material were burning*



Sl. 4. *Konca traku iz nerjavnega jekla (30 x 0,5 mm) s spodnjima robovoma, kjer je gorel oblok za navarjanje notranjosti odprtin na primarni glavi z oznakama 004 in 006 (sl. 1)*
Fig. 4. *Two parts of a stainless strip (30 x 0.5 mm) showing the lower edges at which an arc for cladding the inside of the openings at the primary head designated by numbers 004 and 006 (Fig. 1) was burning*

prehajanja materiala v skupino 1.2.1 - usmerjen prehod [7]. Iz oblike spodnjega robu traka pa je nemogoče oceniti, ali je raztaljeni material prehajal tudi ob steni žlindre. Za razrešitev tega vprašanja bi bilo treba opraviti mnogo več raziskav in uporabiti tudi tehniko presevanja taline vara oziroma varilnega obloka, ki gori pod praškom ([8] do [12], [22]).

Poleg posameznih procesov, ki potekajo med navarjanjem s tračno elektrodo, je zelo pomembna stopnja razmešanja med dodajnim in osnovnim materialom.

Že prej je bilo omenjeno, da je treba doseči navar višine 7,5 do 9,5 mm v več slojih. Širina prekrivanja prejšnjega navara z novim znaša od 7 do 9 mm.

Jakost toka med navarjanjem I je bila približno 650 A, obločna napetost U 30 V in hitrost varjenja v_v 0,11 m/min. Vnos energije na enoto dolžine se izračuna z enačbo:

stitute of Welding) classification, this type of material transfer may be ascribed to group 1.2.1 "guided transfer" [7]. The shape of the lower strip edge does not allow us to assess whether the molten material was also transferred along the slag wall. In order to answer this question several more studies would be needed and an irradiation method should be used for the weld metal and welding arc burning in flux ([8] to [12], [22]).

In addition to the individual processes going on during strip-electrode cladding, the mixing ratio of the filler material and the parent metal is very important too.

As already mentioned, a multilayer cladding with a height of between 7.5 and 9.5 mm was to be obtained. The lap width of the previous cladding with the new one amounted to 7 to 9 mm.

The current intensity during cladding I was around 650 A, the arc voltage U 30 V, and the welding speed v_v 0.11 m/min. Energy input per unit of length can be calculated as follows:

$$E = \frac{I \cdot U}{v_v} \qquad (3)$$

in znaša 1,77 MJ/m, vnos energije na enoto površine pa po naslednji enačbi:

and amounts to 1.77 MJ/m. The heat input per unit of area can be calculated as follows:

$$E = \frac{I \cdot U}{v_v \cdot b_n} \qquad (4).$$

Navarjanje je bilo izvedeno s polom plus na elektrodi, kar je nekoliko neobičajno. Večina literature in praktikov iz industrije, kakor tudi praktične izkušnje avtorjev tega članka, priporoča, da se pri navarjanju s tračno elektrodo priključi pozitivna sponka na varjenec in negativna sponka na elektrodo ([13] do [16]). Način gorenja obloka, globina uvara in talilni učinek so namreč odvisni od polarnosti.

Katodna pega je površina na negativni elektrodi, iz katere izstopajo elektroni za vzdrževanje obloka. Elektroni skozi oblok ionizirajo nevtralno atmosfero in ustvarjajo plazmo. Površino na anodi, tj. na pozitivni elektrodi, na katero priletijo elektroni, imenujemo anodna pega.

Katodna pega je v primerjavi z anodno mnogo gibljivejša, ker po katodi išče najugodnejše mesto za izstop elektronov. Zaradi velike gibljivosti katodne pege se na negativni sponki pretali več materiala kakor na pozitivni, temperatura pa je, zaradi gibanja katodne pege, manjša na negativni sponki kakor na pozitivni. Iz povedanega izhaja, da je primerneje navarjati z negativno sponko na elektrodi, ker se pretali več dodajnega in manj osnovnega materiala.

Z negativno sponko na elektrodi pri navarjanju s tračno elektrodo je mogoče doseči ugodnejšo stopnjo razmešanja. Pri navarjanju malo legiranega konstrukcijskega jekla z nerjavnim avstenitnim jeklom se priporoča stopnja razmešanja od 12 do 15 odstotkov. Izračunamo jo z enačbo:

Cladding was carried out with a positive electrode, which was somewhat unusual. The majority of papers and practitioners in industry as well as the practical experiences of the authors recommend that in strip-electrode cladding the workpiece is positive and the electrode negative ([13] to [16]). The mode of arc burning, penetration depth, and melting rate depend on the polarity.

A cathode spot is the area at the negative electrode from which electrons for arc maintenance are emitted. The electrons passing through the arc, ionise the neutral atmosphere, and generate plasma. The anode area at the positive electrode where the electrons strike is called the anode spot.

The cathode spot is much more mobile than the anode one because it is searching for the most suitable spot for electron emission from the cathode. Because of the great mobility of the cathode spot, more material will be melted at the negative pole than at the positive pole, but the temperature will be lower at the negative pole than at the positive pole. This suggests that it is more appropriate to surface with a negative electrode since a larger volume of the filler material and a lesser volume of the parent metal will be melted.

In strip-electrode cladding it is possible to obtain a more favourable mixing ratio with the electrode negative. In cladding low-alloy structural steel with austenitic stainless steel, a mixing ratio of 12 to 15 % is recommended. It can be calculated as follows:

$$\gamma = \frac{A_0}{A_0 + A_d} \cdot 100 \quad (\%) \tag{5}$$

kjer je:

A_o – površina prečnega prereza navara –staljen osnovni material

A_d – površina prečnega prereza navara –staljen dodajni material

Pri nižjih stopnjah razmešanja lahko pride do luščenja navarjene plasti od osnovnega materiala, pri višjih stopnjah pa do nastajanja martenzitne strukture (glej Schaefflerjev diagram – sl. 2).

Poleg stopnje razmešanja sta od polarnosti odvisna tudi prigor in odgor legirnih elementov med varjenjem.

Treba je dodati, da je navarjanje z negativno sponko na elektrodi predvsem "srednjeevropski" način platiranja nerjavnega jekla na malo legirano konstrukcijsko jeklo ([14] do [16]).

Navarjanje s pozitivno sponko na elektrodi, kakršno je bilo uporabljeno pri izdelavi primarne glave uparjalnikov, pa je ameriška tehnologija navarjanja, ki jo je prevzel tudi ESAB ([15] in [17]). Za navarjanje s pozitivno sponko na elektrodi se zaradi procesov pod praškom in v talini vara uporabljajo trakovi iz nerjavnega avstenitnega jekla, ki so nekoliko močneje legirani.

Za navarjanje notranjosti primarne glave so bili uporabljeni trakovi podjetja SANDVIK in varilni praški podjetja ESAB.

Drugi navari, ki so na sliki 1 označeni s številkami 003, 005, 009 in 012, so narejeni ročno obločno z oplaščeno elektrodo. Tudi v tem primeru je prvi sloj navarjen z elektrodo s splošno oznako 24/13 in drugi z elektrodo z oznako 19/9.

Pri analizi navarjanja pod praškom je zelo pomemben dejavnik tudi produktivnost procesa. Prikažemo ga lahko na več načinov ([7], [18] do [21]). Najjasnejša pokazalnika produktivnosti sta talilni učinek in površinski učinek. Prvi je definiran s količino pretaljenega dodajnega materiala v časovni enoti, drugi pa s količino navarjene površine na časovno enoto.

2 IZDELAVA SPOJA MED CEVJO IN CEVNO STENO

Na izbiro postopka za spajanje cevi v cevno steno najbolj vplivajo obratovalni parametri toplotnega menjalnika. Kakšna sta obratovalni tlak in temperatura? Kako je delovni medij kemično oz. korozijsko agresiven? Ali je varjenje sploh mogoče?

Če je toplotni menjalnik namenjen za obratovanje v kemično oz. korozijsko agresivnem sredstvu ob visokih temperaturah in tlaku, se priporoča izvedba spoja z varjenjem. Za izboljšanje kakovosti spoja se varjenje kombinira z ekspanzijo cevi v cevni steni ([23] in [24]).

where:

A_0 – area of the cross-section of the cladding - molten parent metal

A_d – area of the cross-section of the cladding - molten filler material

With lower mixing ratios, peeling-off of the surface layer from the parent metal may occur, and with higher mixing ratios, formation of a martensite structure (see Schaeffler diagram - Fig. 2).

Polarity affects not only the mixing ratio but also the pick-up and burn-off of alloying elements during welding.

It should be mentioned that cladding with a negative electrode is a Central European practice for cladding stainless steel on low-alloy structural steel ([14] to [16]).

Cladding with a positive electrode, which was used in the fabrication of the primary steam-generator head, however, is an American cladding technology, which was also taken over by the ESAB ([15] and [17]). For cladding with a positive electrode more strongly alloyed strips of austenitic stainless steel are used because of the submerged-arc and weld-pool processes.

For cladding the inside of the primary head, strips manufactured by SANDVIK and welding fluxes manufactured by ESAB were used.

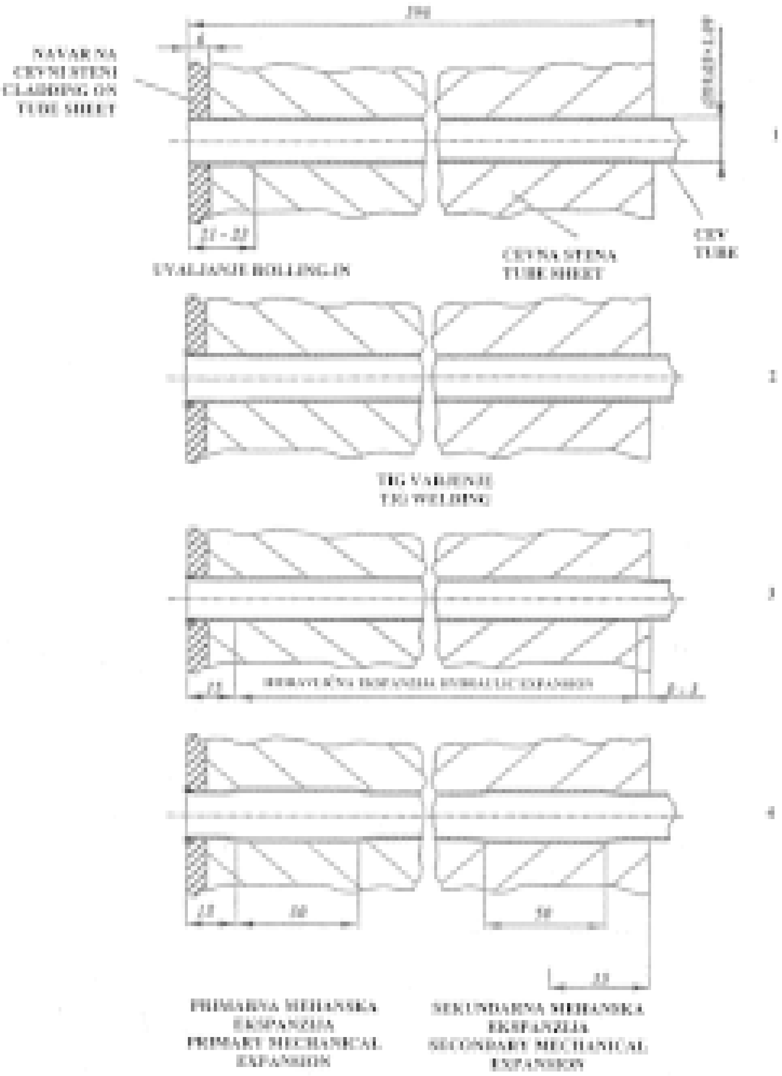
The other claddings, designated with numbers 003, 005, 009, and 012 in Fig. 1, were submerged-arc surfaced with a covered electrode. In this case too, the first layer was surfaced with an electrode having a general designation 24/13, and others with an electrode having a designation 19/9.

In an analysis of submerged arc cladding, process productivity is also an important factor. It can be shown in several ways ([7], [18] to [21]). The most useful indicators of productivity are melting rate and the surface effect. The first is defined as the volume of filler material melted per unit of time, and the second as the size of the area surfaced per unit of time.

2 JOINING THE TUBE TO THE TUBE SHEET

The choice of a procedure for joining tubes to the tube sheet is mainly affected by the operating conditions of the heat exchanger. How high are the operating pressure and operating temperature? How chemically aggressive or corrosive is the working medium? Is welding possible?

If the heat exchanger is designed for operation in chemically aggressive, i.e. corrosive, media at elevated temperatures and pressures, welding is recommended for the joint. To improve joint quality, welding is combined with tube expansion in the tube sheet ([23] and [24]).



Sl. 5. *Potek izvedbe zvarnega spoja med cevjo in cevno steno. 1 - mehansko uvaljanje; 2 - TIG varjenje; 3 - hidravlična ekspanzija; 4 - mehanska ekspanzija.*

Fig. 5. *Execution of the welded joint between a tube and the tube sheet. 1 - mechanical rolling-in; 2 - TIG welding; 3 - hydraulic expansion; 4 - mechanical expansion.*

Spoj med cevno steno in cevmi je najbolj kritičen element uparjalnika, zato se napake najpogosteje pojavljajo prav na njih. Varnost in zanesljivost uparjalnika je odvisna od kakovosti vsakega posameznega spoja med cevjo in cevno steno ([25] in [26]).

Prav zaradi čim večje varnosti in kakovosti spoja je bila izbrana kombinirana metoda varjenja in ekspanzije cevi v izvrtini v cevni steni.

Spoj je bil izveden v štirih korakih, kakor je shematsko prikazano na sliki 5.

- Najprej so bile cevi mehansko uvaljane v dolžini 21 mm od primarne strani cevne stene.
- Priprava zvarnega spoja in varjenje cevi na primarno stran cevne stene, po postopku TIG.
- Sledi hidravlična ekspanzija cevi po vsej dolžini cevne stene.
- Mehanska ekspanzija v dolžini 2x 50 mm.

The joint between the tube sheet and the individual tubes is the most critical element of the steam generator. Consequently, defects are most often found at this joint. The safety and reliability of the steam generator depends on the quality of each individual joint between the tube sheet and the tube ([25] and [26]).

It is for the sake of safety and joint quality that the combined procedure of welding and tube expansion in the borehole of the tube sheet was selected.

The joint was made in four steps as shown in Fig. 5:

- First the tubes were mechanically rolled-in to a length of 21 mm from the primary side of the tube sheet.
- Then the welded joint was prepared and the tube TIG welded at the primary side of the tube sheet.
- Then followed hydraulic expansion of the tube along the whole tube sheet length.
- Finally mechanical expansion was carried out over a length of 2 x 50 mm.

Od varjenja se zahteva, da zagotovi popolno tesnost in zadovoljivo trdnost spoja. Z dvema postopkoma ekspanzije so bile cevi enakomerno uvaljane v izvrtino cevne stene. S tem je bila zaprta špranja med cevmi in izvrtino cevne stene, kjer bi se lahko kopičili radioaktivni in korozijski produkti.

S kombinacijo dveh postopkov ekspanzije so bile, kar zadeva zaostale napetosti, dosežene najugodnejše razmere v ceveh.

2.1 Mehansko uvaljanje cevi

V cevno steno je bilo skozi podporne rešetke na sekundarni strani uparjalnika montiranih 5428 cevi U s premerom 19,05 mm in z debelino stene 1,09 mm. Premer lukenj v cevni steni je bil 19,27 mm. Cevi U so bile nato še mehansko uvaljane v dolžini 21 do 23 mm od primarne strani cevne stene. S tem postopkom so bile cevi U pritrjene v cevno steno, da se je lahko izvedla priprava zvarnega robu. Sila oprijemanja cevi U v cevno steno po mehanskem uvaljanju je bila preverjena na testnih vzorcih. Sila oprijemanja je zadostna, če se cev U ne da izvleči z roko.

S posebnim ekspanzijskim orodjem iz gume je bilo preverjeno, ali so cevi pritrjene v izvrtinah cevne stene in se ne premikajo. S to operacijo se je zaprla vrzel med cevjo U in izvrtino v cevni steni. Za doseganje optimalnih pogojev varjenja je bila oprema za mehansko uvaljanje nastavljena tako, da se cev med pripravo zvarnega robu ni mogla zasukniti. Cevi U so se med uvaljanjem relativno malo deformirale in so imele zato le relativno nizke zaostale napetosti.

2.2 Varjenje

Strojna obdelava zvarnega robu je bila izvedena s posebno frezalno napravo, ki ima tri frezalna rezila premaknjena za 120°. V sredini frezalne naprave je centrirni nastavek dolžine 100 mm, s katerim se naprava pritrdi in centrira v izvrtini, ki jo obdelujemo. Na 1 % izbranih cevi je bila izvedena dimenzionalni nadzor priprave zvarnega robu.

Varjenje cevi U v cevno steno je bilo izvedeno z uporabo avtomatskega varjenja po postopku TIG. Varilni avtomat je napravil zvar v enem prehodu z dodajanjem varilne žice, ki se je talila v obloku in skupaj s cevno steno in cevjo tvorila zvar. Skupni čas, v katerem je varilni avtomat izdelal celoten zvar, je znašal 92 sekund. Namen varjenja je bil zagotoviti popolno tesnost spoja med cevjo in cevno steno.

2.2.1 Pulzni postopek varjenja

S pulznim načinom varjenja po načinu TIG se lahko nadzira vnos toplote v zvar. Ta postopek ponuja kar nekaj prednosti pred običajnim načinom varjenja:

Welding is required to assure 100 % tightness and a satisfactory joint strength. With two expansion procedures the tubes were uniformly rolled into the tube-sheet boreholes. Thus the gap between the tube and the tube-sheet borehole, in which radioactive and corrosive products could pile up, was closed.

The combination of the two expansion procedures provided the most favourable conditions concerning the residual stresses in the tubes

2.1 Mechanical rolling-in of the tubes

5428 U tubes with a diameter of 19.05 mm and a wall thickness of 1.09 mm were mounted into the tube sheet through supporting grids on the secondary side of the steam generator. This operation is called tubing. The diameter of the tube-sheet holes was 19.27 mm. The U tubes were then mechanically rolled to a length of 21 to 23 mm from the primary side of the tube sheet. Using this procedure, the tubes were fixed into the tube sheet so that the edge preparation could be made. After mechanical rolling-in, adhesion of the U tubes was verified on test pieces. The adhesion is sufficient if a U tube cannot be pulled out by a human hand.

A special expansion tool made of rubber was used to check whether the tubes were fixed in the tube-sheet boreholes and could not be moved. Thus the gap between the U tube and the tube-sheet borehole was closed. In order to obtain optimum welding conditions, the equipment for mechanical rolling-in was set so that the tube could not turn a round during weld edge preparation. The U tubes were comparatively undeformed during rolling-in and consequently showed comparatively low residual stresses.

2.2 Welding

Machining of the weld edge was carried out by a special milling machine having three milling blades each staggered by 120°. In the centre of the milling machine there was a centring boss with a length of 100 mm with which the machine was fixed and centred in the borehole to be machined. 1 % of the selected tubes were examined as to the dimensions of the weld-edge preparation.

The U tubes were automatically TIG welded into the tube sheet. An automatic welder made a single-run weld with the addition of a welding wire which melted in the arc and constituted the weld jointly with the tube sheet and the tube. The automatic welder made the weld in 92 seconds. The purpose of welding was to achieve absolute tightness of the tube-to-tube sheet joint.

2.2.1 Pulsed-welding process

Pulsed TIG welding permits control of heat input. It offers a number of advantages over a conventional welding process, i.e.:

- možnost nadzora prostornine taline vara,
- večja globina uvara ob enakem vnosu energije,
- hitrost varjenja je mogoče nadzirati z varilnimi parametri,
- lažje razplinjevanje in s tem boljša kakovost,
- manjša obremenitev volframove elektrode.

Pulzno-tokovni način varjenja je postopek, v katerem se varilni tok zvezno spreminja med dvema nastavljenima vrednostima. V času trajanja pulznega toka potekata segrevanje in taljenje, v času pretoka osnovnega toka pa hlajenje in strjevanje taline. Vir varilnega toka samodejno preklaplja med pulznim in osnovnim varilnim tokom in obdrži želeno vrednost za določen čas. S pulznim postopkom naredimo celoten zvar s prelitjem teh posameznih delov vara, tako da se elektroda zvezno giblje po zvarnem robu. Potek jakosti toka med varjenjem je prikazan na sliki 6.

Pomembne veličine, ki jih lahko nastavimo in nadziramo, so:
- jakost pulznega toka,
- jakost osnovnega toka
- čas trajanja pulznega toka,
- čas trajanja osnovnega toka,
- oblika pulza,
- hitrost varjenja.

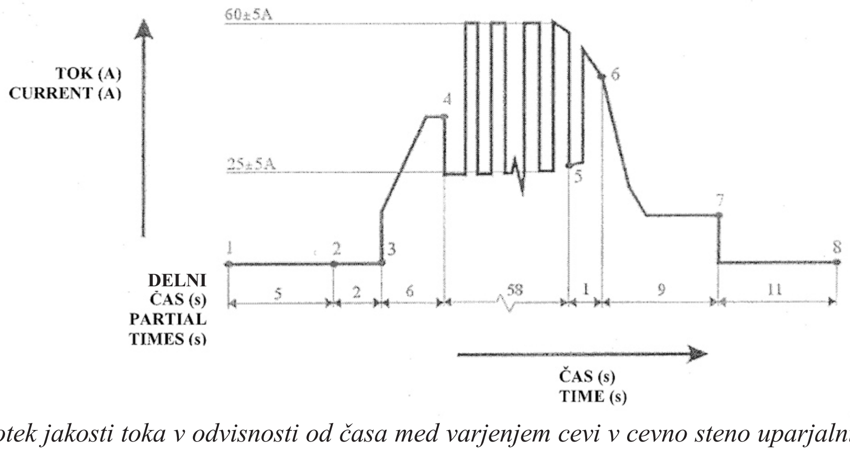
Viri varilnega toka za varjenje po pulznem postopku imajo možnost za natančno nastavitev teh veličin. Vrednost pulznega toka je približno 1,5 do 2–krat večja od normalnega varilnega toka za taka dela. Osnovni tok je potreben le za ohranjanje stabilnega gorenja obloka. Običajno je ta jakost nastavljena na eno četrtino vrednosti jakosti pulznega toka.

- the possibility of control over the weld metal volume,
- deeper penetration with the same heat input,
- welding speed can be controlled by welding parameters,
- better degassing and, consequently, higher quality,
- smaller load of a tungsten electrode.

A pulsed-current welding process is a method in which the welding current continuously varies between two preset values. During the pulsed-current flow heating and melting occur, and during the background-current flow cooling and weld-pool solidification take place. The welding current source will automatically switch between the pulse and the background welding currents and maintain, for a certain time, the required value. With the pulse process the weld is completed by overflowing individual parts of the weld by a continuous movement of the electrode along the weld edge. The current variation during welding is shown in Fig. 6.

Important quantities which may be set and controlled are the following:
- pulsed-current intensity,
- background-current intensity,
- pulsed-current duration,
- background-current duration,
- pulse shape,
- welding speed.

Welding current sources designed for the pulsed-current method offer the possibility of a very accurate setting for the quantities concerned. The pulsed current is approximately 1.5 to 2.0 times the normal welding current for such work. The background current is needed only for maintenance of stable arc burning. Usually this intensity is set to be one quarter of the pulsed-current intensity.



Sl. 6. *Potek jakosti toka v odvisnosti od časa med varjenjem cevi v cevno steno uparjalnika po postopku TIG. 1 - začetek procesa s pretokom plina; 2 - vključitev visoke frekvence za vžig obloka; 3 - začetek varjenja in oblikovanje taline; 4 - pričetek gibanja varilne pištole in varilne žice; 5 - začetek prekrivanja začetnega dela vara; 6 - zmanjševanje jakosti toka in ustavitev dodajanja žice; 7 - konec varilnega procesa; 8 - prekinitev dovajanja plina.*

Fig. 6. *Current variation as a function of time during TIG welding of a tube into the tube sheet of the steam generator. 1 - process start with gas flow; 2 - switching of high frequency for arc ignition; 3 - start of welding and molten-pool formation; 4 - start of gun movement and welding wire; 5 - beginning of overlap of the initial part of the weld; 6 - decrease of current intensity and stoppage of wire feed; 7 - end of welding process; 8 - interruption of gas supply*

Čas trajanja pulznega toka je nastavljen tako, da omogoča nastanek talilne kopeli z želeno globino uvara. Ta čas je po navadi nekje med 0,2 in 1 sekundo. Čas trajanja osnovnega toka je nastavljen tako, da je omogočeno delno strjevanje talilne kopeli. S pravilnimi nastavitvami je mogoče nadzirati talilno kopel, dimenzije varka in globino uvara. Varilec lahko spreminja nastavitve, za doseganje optimalnega varjenja, v odvisnosti od osnovnega materiala, debeline osnovnega materiala, lege varjenja, oblike zvarnega spoja. Dodajni material se pripelje na mesto varjenja v obliki žice, navite v kolut. Jakost toka mora biti tako krmiljena, da v času pulza iz žice v talino vara preide raztaljena kapljica.

Zvarni spoj se izvede med naslednjima dvema osnovnima materialoma:

- toplotno obdelano zlitino inconel 690, iz katere so izdelane cevi U z debelino stene 1,09 mm, in
- 6 mm debelo plastjo inconela, ki je navarjena na osnovni material cevne stene SA-508 razred 3a debeline 590 mm.

Dodajni material je žica ER Ni Cr-3 s premerom 0,6 mm. Kemične sestave osnovnih in dodajnih materialov so prikazane v preglednici 1.

Na sliki 7 je prikazan makro obrus zvarnega spoja med cevjo in cevno steno, izdelanega po postopku TIG. Z oznako (1) je označena stena cevi s premerom 19,05 mm in debelino 1,09 mm. Cevna stena je bila navarjena v več slojih, podobno kakor primarna glava, le da je bil tu uporabljen inconel kot dodajni material. Zgornji sloj je označen s številko (2). Zvar, ki tvori zvarni spoj med cevjo in cevno steno, je označen s številko (3). Zvar je bil narejen v eni potezi, toda makro obrus prikazuje mesto, kjer se je varjenje začelo in končalo, kar pomeni, da se začetek in konec vara prekrivata.

2.3 Ekspanzija cevi v cevni steni

Ekspanzija cevi v cevni steni je deformacijski proces, pri katerem se material utrjuje,

Pulsed current duration is set so as to permit the formation of a weld pool with a required penetration depth. This usually amounts to 0.2 to 1 second. The background-current duration is set so as to permit partial solidification of the weld pool. Appropriate settings make it possible to control the weld pool, weld-pass dimensions, and penetration depth. A welder may change the settings with regard to the parent metal, parent metal thickness, welding position, welded-joint shape to achieve optimum welding. The filler material used for welding is a wire in a coil form. The current intensity should be controlled so that a molten droplet is transferred from the wire into the weld pool during the pulse duration.

The welded joint was formed between the following two materials:

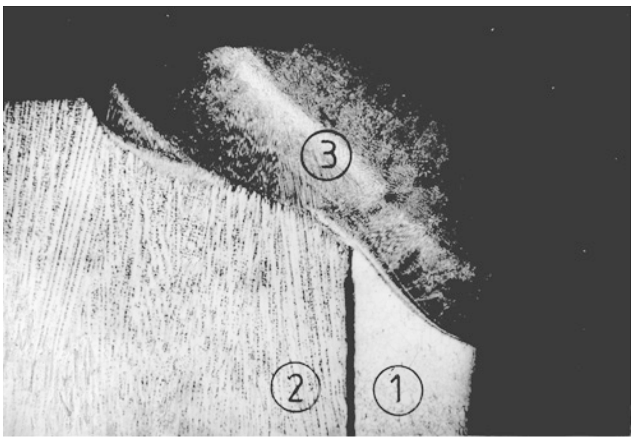
- heat-treated alloy Inconel 690, of which the U tubes with a wall thickness of 1.09 mm were made,
- 6 mm thick Inconel layer which was surfaced on the parent metal of the tube sheet SA-508 Class 3a with 590 mm thickness.

The filler material used was the wire ER Ni Cr-3 with a 0.6 mm diameter. Chemical compositions of the parent metal and the filler materials are shown in Table 1.

Fig. 7 shows a macro specimen of the TIG-welded joint between a tube and the tube sheet. Designation (1) indicates the tube with a diameter of 19.05 mm and a thickness of 1.09 mm. The tube sheet was surfaced with several layers, similar to the primary head, with the exception of the filler material which was Inconel in this case. The upper layer is designated as (2). The weld making the welded joint between the tube and the tube sheet is designated as (3). The weld was made in a single pass. The macro section, however, shows the location where welding began and finished, thus the beginning and the end of the weld overlap.

2.3 Tube expansion in the tube sheet

Tube expansion in the tube sheet is a process of deformation in which a material will harden



Sl. 7. *Makro obrus zvara zvarnega spoja cevi s cevno steno*
Fig. 7. *Macro specimen of the welded joint between a tube and the tube sheet*

kristalna zrna pa se deformirajo. Posledica tega so sorazmerno visoke napetosti in delno raztezanje cevi, kar lahko povzroči dodatne napetosti.

Osnovno načelo ekspanzije cevi je, da z velikо pritisno silo med orodjem in steno cevi presežemo mejo elastičnosti materiala cevi. Pride do plastične deformacije cevi, ki se konča, ko pride do stika med cevjo in izvrtino cevne stene. Tudi cevna stena prestane manjšo elastično deformacijo. Ko umaknemo orodje iz cevi, ta povratna elastična deformacija cevne stene povzroči trajen stik med cevjo in izvrtino cevne stene [25].

Ekspanzija cevi je bila v našem primeru izvedena v dveh korakih, in sicer najprej hidravlična, nato pa še mehanska ekspanzija. S tem je bil kar najbolj zmanjšan učinek špranje na sekundarni strani cevne stene, ki bi lahko nastala med izvrtino cevne stene in cevjo. V špranji bi se lahko kopičili radioaktivni in korozijski delci, kar bi lahko povzročalo nadaljnje korozijske procese. Varnost in zanesljivost uparjalnika je odvisna od kakovosti vsakega posameznega spoja med cevjo in cevno steno. Strukturo spoja se določi glede na zahtevani mehansko trdnost in tesnost.

2.3.1 Hidravlična ekspanzija

Hidravlično preoblikovanje je razmeroma nov postopek za ekspandiranje cevi v cevno steno. Postopek so razvili v podjetju Balcke-Dürr AG v Nemčiji, danes pa ga uporablja že veliko proizvajalcev. Z natančnim nadzorom delovnega pritiska (okoli 300 bar) lahko dosežemo manjše vrednosti zaostalih napetosti kakor pri drugih postopkih. Prav tako se skrajša čas, potreben za ekspanzijo ene cevi.

Področje hidravlične ekspanzije se je pričelo približno 10 mm od primarne strani cevne stene in se je nadaljevalo po vsej debelini cevne stene, končalo pa v območju 0 do 3 mm od roba sekundarne strani cevne stene.

Ekspandirani spoji morajo imeti gladko površino [26]. Posebej je treba paziti, da ne ekspandiramo cevi zunaj področja cevne stene, ker bi močno poškodovali cevi. Tako cev bi bilo treba začepiti in izločiti iz uporabe.

Delovni tlak vode je bil z uporabo črpalnega sistema nastavljen na 2500 bar. Na trn so bili montirani trije vrteči se valji. Skozi trn se je tlak vode prenesel na valje, ki so plastično deformirali steno cevi radialno v izvrtino cevne stene. Tlak je bil zadržan znotraj ekspandirane cevi s pomočjo elastičnega tesnila in segmentnega obroča. Hidravlični sistem je bil elektronsko nadziran.

2.3.2 Mehanska ekspanzija

Po opravljeni hidravlični ekspanziji je bila izvedena še lokalna mehanska ekspanzija z

and crystal line grains will deform. It results in comparatively high stresses and a partial tube expansion, which may produce additional stresses.

A basic principle of tube expansion is to exceed the elastic limit of the material concerned by applying a strong force, with a tool, to the tube wall. Thus plastic deformation of the tube occurs. It will end when the tube touches the tube-sheet borehole. Also the tube sheet suffers a minor elastic deformation. When the tool is removed from the tube, elastic straightening produces a constant contact between the tube and the tube-sheet borehole [25].

In our case, tube expansion was carried out in two steps, i.e., first a hydraulic expansion, then a mechanical expansion. This procedure minimised the gap effect on the secondary side of the tube sheet which might occur between the tube-sheet borehole and the tube. In the gap, radioactive and corrosive particles might accumulate and promote further corrosion processes. The safety and reliability of the steam generator depend on the quality of each individual joint between the tube and the tube sheet. The joint structure was determined with regard to the mechanical strength and the tightness required.

2.3.1 Hydraulic expansion

Hydraulic pressure forming is a new method of tube expansion in the tube sheet. It has been developed by Balcke-Dürr AG in Germany. A number of manufacturers have already introduced it into their manufacturing. An accurate supervision of working pressure (around 300 bar) allows us to obtain lower values of residual stresses than with other methods. The time required for tube expansion is shorter as well.

The zone of hydraulic pressure expansion started around 10 mm from the primary side of the tube sheet, continued through the tube-sheet thickness, and ended 0 to 3 mm from the edge of the secondary side of the tube sheet.

The expanded joints should have a smooth surface [26]. Particular attention should be paid to ensure the tubes are not expanded outside the zone of the tube sheet because the tubes could become damaged. Such a tube should be plugged and eliminated from use.

The working pressure of water is set to 2500 bar by a pumping system. Three rotating cylinders are mounted on a mandrel. Through the mandrel the water pressure is transmitted to the cylinders which plastically deform the tube wall in the direction radial to the tube-sheet borehole. The pressure inside the expanded tube is maintained by means of an elastic seal and a segment ring. The hydraulic pressure system is electronically monitored.

2.3.2 Mechanical expansion

After hydraulic pressure expansion, also local mechanical expansion is performed in order to namenom, da cevi v cevno steno še dodatno pritrdijo in se zagotovijo ugodne razmere na obeh robovih ekspandiranega področja. Dolžina mehansko ekspandiranega področja je 50 mm na obeh straneh cevne stene [27]. Za mehansko ekspanzijo uporabljamo osno vzporedne valje s hidravličnim trnom. Moment se prenaša iz ekspanzijskega stroja prek osi na trn orodja [28].

additionally fix the tube into the tube sheet and ensure favourable conditions at both edges of the expanded zone. The mechanically expanded zone is 50 mm long at each side of the tube sheet [27]. For mechanical expansion, axially parallel cylinders with a hydraulic mandrel are used. The torque was transmitted from the expansion machine via the axis to the tool mandrel [28].

3 VARJENJE PREDELNE STENE NA PRIMARNO GLAVO IN CEVNO STENO

Predelna stena med primarno glavo in cevno steno deli primarno komoro na vroči in hladni del (sl. 1). Izdelana je iz inconela 690 in privarjena na primarno glavo in cevno steno. Zaradi zahtevnosti montaže je bila izdelana iz treh delov, ki so bili zvarjeni med montažo v primarni komori. Izdelava zvarnih spojev med predelno steno in primarno glavo ter predelno steno in cevno steno je bila izjemno zahtevna operacija zaradi različnosti materialov, medtem ko zvarjanje posameznih elementov predelne stene ni delalo posebnih težav.

Makro obrus zvarnega spoja med predelno steno in primarno glavo je prikazan na sliki 8.

Spodnji del spoja (1 – sl. 8) predstavlja primarno glavo, na kateri je bil prvi sloj varjen z avstenitnim nerjavnim jeklom 24/13 (3 – sl. 8) in druga dva z avstenitnim nerjavnim jeklom 19/9 (4 – sl. 8), kakor je opisano pod točko 1.2.

Na navar iz nerjavnega jekla je bila nato navarjena vmesna plast (5 – slika 8) iz inconela 182. Ta plast je bila navarjena ročno obločno z oplaščenimi elektrodami. Tudi predelna stena se je nato na plast namaz zvarila ročno obločno z oplaščenimi elektrodami (6 – sl. 8).

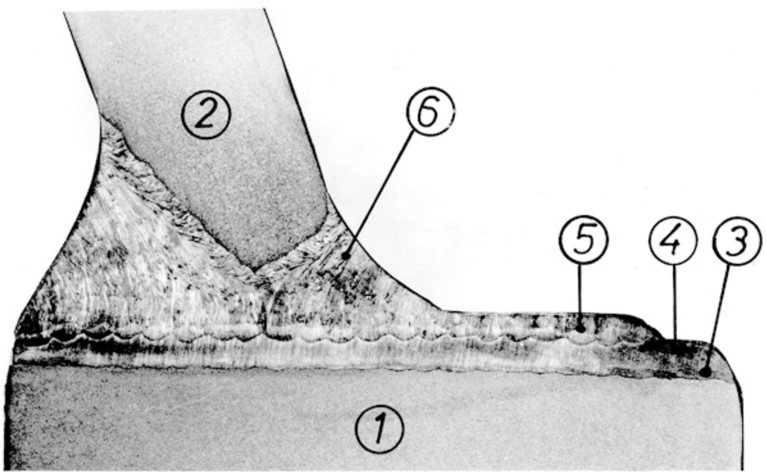
3 WELDING OF THE PARTITION PLATE TO THE PRIMARY HEAD AND THE TUBE SHEET

The partition plate between the primary head and the tube sheet separates the primary chamber into hot and cold parts (Fig. 1). It is made of Inconel 690 and welded to the primary head and the tube sheet. Because of the exacting assembly, it is made of three parts which were welded during assembly in the primary chamber. Making the welded joints between the partition plate and the primary head and between the partition plate and the tube sheet was an extremely exacting operation because of the differences in the materials used. Welding of individual elements of the partition plate, however, was not problematic.

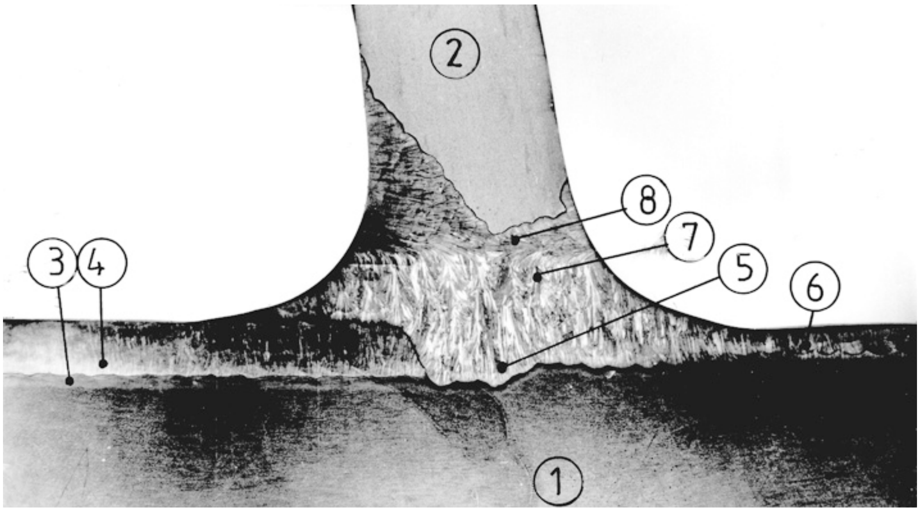
A macro specimen of the welded joint between the partition plate and the primary head is shown in Fig. 8.

The lower part of the joint (1 - Fig. 8) represents the primary head at which the first layer was welded with austenitic stainless steel 24/13 (3 - Fig. 8) and the other two with austenitic stainless steel 19/9 (4 - Fig. 8) as already described in section 1.2.

On the stainless-steel cladding an intermediate layer of Inconel 182 was then surfaced (5 - Fig. 8). This layer was manually arc surfaced with covered electrodes. Also the partition plate was then manually arc welded on the “buttering” layer with covered electrodes (6 - Fig. 8).



Sl. 8. *Makro obrus zvarnega spoja med primarno glavo in predelno steno primarne komore uparjalnika*
Fig. 8. *Macro specimen of the welded joint between the primary head and the partition plate of the primary chamber of the steam generator*



Sl. 9. *Makro obrus zvarnega spoja med predelno in cevno steno*
Fig. 9. *Macro specimen of the welded joint between the partitian plate and tube sheet*

Drugi zvarni spoj med predelno in cevno steno je bil izdelan nekoliko drugače. Makro obrus testnega odrezka za kvalifikacijo postopka vidimo na sliki 9.

Že v točki 3 smo zapisali, da je cevna stena izdelana iz enakega materiala kakor primarna glava (pregl. 1). Cevna stena (2 – sl. 9) je bila nato navarjena s trakom pod praškom, podobno kakor primarna glava, toda z nekoliko različnimi materiali. Navar v dveh slojih iz nerjavnih jekel je na sliki 9 označen s številkama 3 in 4. Zaradi čim boljše izenačitve lastnosti materialov je bila na navar iz nerjavnega jekla navarjena plast iz inconela v več slojih (5, 6 in 7 – sl. 9). V vseh primerih se je navarjalo z inconelom 182 z oplaščeno elektrodo po postopku ročno obločno varjenje. Zvar med cevno steno, ki je izdelana iz inconela 690, in navarjeno plastjo iz inconela 182 je bil izveden ročno obločno z oplaščenimi elektrodami z inconelom 182 (8 – sl. 9). Koren vara je bil varjen z elektrodo premera 3,25 mm, jakostjo toka 95 do 100 A in napetostjo obloka 25 V. Preostali varki so bili izdelani z elektrodo premera 4 mm, jakostjo toka 135 A in obločno napetostjo 26 V. Elektrode so bile pred uporabo sušene in nato skladiščene v posebni prenosni pečici, da jih je varilec jemal iz nje tik pred pričetkom varjenja.

Analiza testnega odrezka je pokazala, da je cevno steno najprimerneje navariti z inconelom brez vmesne plasti iz nerjavnega jekla. Navarjanje je bilo izvedeno s tračno elektrodo in ročno obločno z oplaščeno elektrodo.

4 VARJENJE KROŽNIH VAROV NA PLAŠČU UPARJALNIKA

Zunanji plašč uparjalnika ni enakega premera po vsej dolžini. Spodnji del ima premer 3452 mm in debelino stene 74 mm, zgornji pa premer 4474

The second welded joint, i.e., between the partition plate and the tube sheet, was made in a different manner. A macro specimen of the test coupon for procedure qualification is shown in Fig. 9.

As already mentioned, the tube sheet is made of the same material as the primary head (see Table 1). The tube sheet (2 - Fig. 9) was then submerged-arc surfaced with a strip electrode, in the same way as the primary head, but with somewhat different materials. The cladding, consisting of two stainless-steel layers, has designations 3 and 4 in Fig. 9. In order to match the properties of the materials as well as possible, a layer of Inconel was surfaced on the stainless-steel cladding in several layers (5, 6, 7 - Fig. 9). In all the cases, manual-arc cladding with Inconel 182 was carried out with a covered electrode. The weld between the tube sheet made of Inconel 690 and the surfaced layer of Inconel 182 was manually arc welded with covered electrodes of Inconel 182 (8 - Fig. 9).The weld root was welded with an electrode having a 3.25 mm diameter, a current intensity of 95 to 100 A and an arc voltage of 25 V. The other passes were made with an electrode of 4 mm diameter, current intensity of 135 A and arc voltage of 26 V. All the electrodes used were dried prior to use and then stored in a special transportable oven for a welder to take them out immediately before welding.

An analysis of the test coupon showed that it was best to surface the tube sheet with Inconel without the intermediate layer of stainless steel. Cladding was carried out with a strip electrode and manual-arc welding with a covered electrode.

4 WELDING OF CIRCUMFERENTIAL WELDS AT THE STEAM-GENERATOR SHELL

The outer shell of the steam generator does not have the same diameter along the total length. The lower part has a diameter of 3452 mm and wall mm in debelino stene 92 mm. V celoti je izdelan iz enakega materiala kot primarna glava (pregl. 1).

Vsi valjasti deli plašča so bili izdelani s kovanjem, tako da ni vzdolžnih varov. Posamezni deli plašča so bili med seboj spojeni z varjenjem s krožnimi vari.

Koren zvara na delu plašča z večjim premerom je bil najprej zavarjen ročno obločno z zunanje strani (brez prevaritve); pri tem je bila preverjena poravnava. Nato je bil z notranje strani zapolnjen žleb po ročnem obločnem postopku. Zvar je bil z zunanje strani izžlebljen, preverjeni pa so bili profili žleba. Površina zvarnega žleba je bila nato pregledana s tekočimi penetranti. Na koncu je bil zvar z zunanje strani zavarjen po avtomatskem postopku EPP.

Ročno obločno varjenje je bilo izvedeno v primeru elektrode s premerom 3,25 mm z jakostjo toka okoli 110 A, napetostjo približno 25 V in hitrostjo varjenja med 100 in 200 mm/min; v primeru elektrode s premerom 4 mm je bila jakost toka okoli 140 A, napetost približno 26 V in hitrost varjenja med 150 in 250 mm/min.

Postopek varjenja EPP je bil z jakostjo toka okoli 510 A in napetostjo približno 30 V. Hitrost varjenja je bila 0,5 m/min. Vnos energije pri postopku EPP je bil med 1,8 in 1,9 MJ/m.

Vrtenje uparjalnika okoli njegove vzdolžne osi je bilo zagotovljeno z obračalnimi valjčki. Zvarni spoj je bil ves čas ogrevan na 150 °C, tako da ni prišlo do zakaljenih struktur v toplotno vplivanem področju. Višina temperature je bila predpisana z varilnim postopkom. Ogrevanje je bilo izvedeno plamensko z dvema polkrožnima gorilnikoma z vsake strani zvara, ki sta objemala več ko polovico obsega zvara. Temperatura ogrevanja in medvarkovna temperatura sta bili preverjani s kalibriranimi pirometri vsako uro. Med varjenjem in po njem je bila skladno s popisom postopka varjenja izvedena še toplotna obdelava s pogrevanjem na 260 °C za štiri ure za zmanjšanje deleža vodika in notranjih napetosti v zvaru.

Za ročno obločno varjenje so bile uporabljene elektrode SFA-5.5 E9018-G s premerom 3,25 in 4 mm, za postopek EPP pa aglomeriran bazični prašek UV 420 TTR v kombinaciji z žico UNION S3NiMo1, EF3 po SFA A 5.23, s premerom 4 mm, ki je izdelek podjetja Thyssen.

Varjenju je sledilo vse zahtevano preverjanje, tj. VT, RT, MT, UT in brušenje zvara. Zvar je bil lokalno toplotno obdelan, tj. eno uro pri 600 °C. Toplotna obdelava zvara je bila izvedena z elektrouporovnimi grelniki, nameščenimi okoli zvara. Vsi zvari so bili po toplotni obdelavi pregledani z ultrazvokom, in sicer v prvi vrsti za odkritje morebitnih razpok.

Za potrditev ustreznosti varilne tehnologije in pripravo testnih blokov za ultrazvočne preglede

thickness of 74 mm, the upper part, however, has a 4474 mm diameter and a 92 mm wall thickness. It was made of the same material as the primary head (see Table 1).

All cylindrical parts of the shell were made by forging so that there are no longitudinal welds. Individual shell segments were joined by circumferential welds.

The weld root at the shell part having the wider diameter was first manually arc-tack welded from the outside. The alignment was checked. Then the groove was filled by manual-arc welding from the inside. The weld was grooved from the outside and the groove profiles were checked. The surface of the weld groove was subjected to a liquid penetrant examination. Finally, the weld was made from the outside by automatic submerged-arc welding.

Manual-arc welding was carried out with a current intensity of about 110 A, voltage of about 25 V, welding speed varying between 100 and 200 mm/min with an electrode diameter of 3.25 mm, a current intensity of 140 A, voltage of about 26 V and a welding speed varying between 150 and 250 mm/min with an electrode diameter of 4 mm.

Submerged-arc welding was carried out with a current intensity of about 510 A, voltage about 30 V, welding speed of 0.5 m/min and heat input varying between 1.8 and 1.9 MJ/m.

Rotation of the steam generator around its longitudinal axis was provided by rotating rolls. All the time the welded joint was preheated to 150 °C so that no through-hardened structures in the heat-affected zone occurred. The temperature was specified by the welding procedure. Flame heating was carried out with two semicircular burners from each side of the weld, which encompassed more than half of the weld circumference. Preheating and interpass temperatures were compared to calibrated pyrometers each hour. In accordance with the welding procedure specification, heat treatment with soaking to 260 °C for four hours was carried out during and after welding in order to reduce hydrogen content and internal stresses in the weld.

For manual-arc welding electrodes, SFA-5.5 E9018-G with diameters of 3.25 mm and 4 mm were used. For submerged-arc welding an agglomerated basic flux UV 420 TTR was used in combination with a wire UNION S3NiMo1, EF3 according to SFA A 5.23 with a diameter of 4 mm, produced by Thyssen, was used.

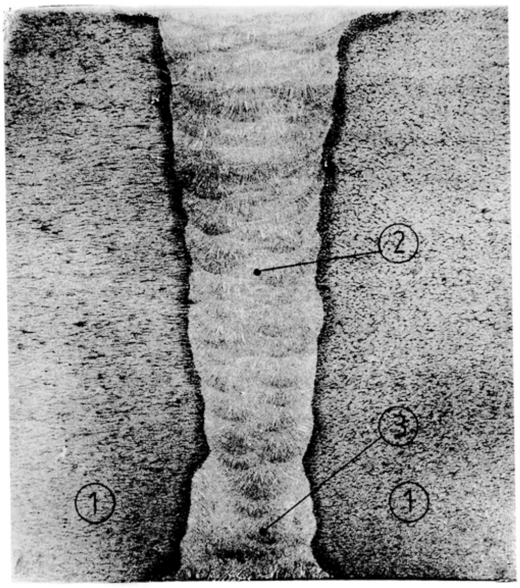
Welding was followed by the control required, i.e. visual inspection, radiographic examination, magnetic particle examination, ultrasonic examination, and weld grinding. The weld was locally heat treated for one hour at a temperature of 600 °C. The weld heat treatment was carried out with electric resistance heaters arranged around the weld. After heat treatment all the welds were examined by ultrasound, primarily in order to detect eventual cracks.

In order to confirm the suitability of the welding technology and to prepare test blocks for so bili zavarjeni testni kuponi z dolžino približno 1000 mm za vsak tip zvara posebej. Postopek izdelave in preverjanja je bil enak kakor pri varjenju na uparjalniku.

Makro obrus zvarnega spoja na zunanjem širšem delu plašča je prikazan na sliki 10. S številko 1 sta označena segmenta zunanjega plašča, s številko 2 var, ki je bil varjen pod praškom v več varkih, in s številko 3 var, ki je varjen ročno obločno z oplaščeno elektrodo.

ultrasonic examination, test coupons of 100 mm in length were welded separately for each weld type. The production and control procedures were the same as for welding the steam generator.

The macro specimen at the outside, wider part, of the shell is shown in Fig. 10. Number 1 designates two segments of the outer shell, number 2 the weld, which was multi-layer submerged-arc welded, and number 3 the weld which was manually arc welded with a covered electrode.



Sl. 10. *Makro obrus zvarnega spoja dveh delov zunanjega širšega premera plašča uparjalnika*
Fig. 10. *Macro specimen of the welded joint between two segments of the steam-generator shell with the outer, wider diameter*

5 SKLEPI

Splošno rečeno je izdelava uparjalnikov vrhunska in najzahtevnejša tehnologija na področju varjenja. To trditev lahko potrdimo s tehnološkega, metalurškega in tudi ekonomskega vidika. Dodana vrednost je izjemno visoka, zato lahko to tehnologijo prištevamo med tako imenovane zahtevne tehnologije.

Zelo velik poudarek je na kakovosti del in izdelkov. Za vsako, na prvi pogled še tako nepomembno opravilo, so bili napisani posebni postopki, po katerih so se morali ravnati izdelovalci. Za zahtevna varilska dela pa so bili izdelani tudi atesti postopkov in preverjeni atesti osnovnih in dodajnih materialov. Vsi izvajalci so morali imeti ustrezne ateste. Nadzor je bil predpisan na vseh ravneh in od različnih ustanov. Prav tako je bil zagotovljen tudi nadzor, ki je bil neodvisen od naročnika in od izvajalca.

Vse to je zagotovilo, da so bili uparjalniki za Jedrsko elektrarno Krško izdelani kakovostno, na najvišjem možnem nivoju, in da bo Jedrska elektrarna Krško tudi v prihodnje, po zamenjavi uparjalnikov, delovala tako varno in uspešno kakor doslej.

5 CONCLUSIONS

Generally it may be stated that the manufacturing of steam generators is the highest and most exacting technology in the field of welding. This statement is true from the viewpoint of technology, metallurgy as well as economy. The value added to the product is extremely high. Consequently, this technology must be considered high technology.

Great stress was laid upon the quality of work and products. For each procedure to be carried out, as unimportant as it may seem at first sight, there was a procedure specification, which should be followed by the manufacturers involved. For exacting welding work, welding procedure tests were carried out, and quality approval tests for parent metals and filler materials were verified. All the manufacturers involved should have certificates of their competence for the work. Testing is prescribed at all levels and by different institutions. Testing independent of the client and the manufacturer, was ensured as well.

This gave us the assurance that the steam generators for the Krško Nuclear Power Plant were manufactured with the required quality and that they would operate safely and efficiently.

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Nova uparjalnika za Jedrsko elektrarno Krško

The New Steam Generators for the Krško Nuclear Power Plant

Krešimir Nemčić

Članek predstavlja nova uparjalnika za JE Krško in opisuje glavne izboljšave projekta in izdelave, ki so kot del stalnega napredka pri razvoju tehnologije uparjalnikov namenjene predvsem večji zanesljivosti in lažjemu vzdrževanju novih uparjalnikov.

Članek tudi podaja osnovne informacije o izdelavi novih uparjalnikov.

(Ključne besede: uparjalniki, Inconel 690TT, ekspanzija, izločevalniki vlage)

This paper presents the new steam generators for the Krško nuclear power plant and describes the main design and fabrication improvements, which are an ongoing research and development effort in steam-generator technology, aimed at improving the reliability and maintainability of the new steam generators.

The paper also provides basic information relating to the manufacturing of the new steam generators.

(Keywords: steam generators, Inconel 690TT, expansion, moisture separators)

0 UVOD

Pogodba za izdelavo novih uparjalnikov je bila sklenjena s Konzorcijem Siemens Framatome. Drugi ponudniki so bili: Westinghouse, ZDA, Babcock & Wilcox, Kanada in Mitsubishi, Japonska. Konzorcij Siemens Framatome je bil izbran na podlagi izpolnjevanja zahtev, ki so bile določene v nabavni specifikaciji in vrednotene na podlagi štirih glavnih kriterijev: dolgoročna zanesljivost tlačne meje, ekonomska upravičenost, zmogljivost uparjalnikov in datum izročitve.

Pred JE Krško so že druge evropske jedrske elektrarne kot nadomestilo za dotrajane Westinghousove uparjalnike izbrale Siemens oz. konzorcij Siemens Framatome. Te elektrarne so: Ringhals 2 in 3 na Švedskem, ASCO 1 in 2 ter Almaraz 1 in 2 iz Španije, Doel 3 iz Belgije.

Nova uparjalnika sta bila izdelana in izročena v 33 mesecih, vključno z njunim transportom iz Santanderja v Španiji do Krškega, kakor je zahtevala pogodba.

Uparjalnika Konzorcija Siemens Framatome sta izdelana v skladu z zahtevami ASME pravilnika o vrelnih in tlačnih posodah, Del III,

0 INTRODUCTION

The contract for manufacturing the new steam generators for the Krško nuclear power plant (NPP) was with the Consortium Siemens-Framatome. The other bidders were Westinghouse (USA), Babcock&Wilcox (Canada) and Mitsubishi (Japan). The consortium Siemens-Framatome was chosen because it best fulfilled the requirements that were specified in the procurement specification and which were evaluated in four areas: long term reliability of the pressure boundary, economy, steam-generator capability and delivery date.

Prior to Krško NPP's decision, other European NPPs had ordered Siemens or Consortium Siemens-Framatome designed steam generators as replacements for the original Westinghouse steam generators. These plants are: Ringhals 2&3 in Sweden, ASCO 1&2 and Almaraz 1&2 in Spain, Doel 3 in Belgium.

The new steam generators were manufactured and delivered in 33 months, this included the transport of the steam generators from Santander in Spain to Krško, as specified in the contract.

The steam generators delivered by Consortium Siemens-Framatome were designed in accordance with the requirements of the ASME Boiler &

Oddelek 1, Podskupina NB, kot komponenti razreda 1. Komponente razreda 1 so tiste, ki sestavljajo tlačno mejo reaktorskega hladila.

Dotrajane stare uparjalnike je treba zamenjati predvsem zaradi velikega števila poškodovanih cevi in s tem povezanimi stroški vzdrževanja. Pri projektiranju in izdelavi novih uparjalnikov smo zato predvideli precejšnje število sprememb, ki bodo povečale odpornost proti poškodbam. Ker na nastanek poškodb najbolj vplivajo: materiali, okolje (tj. predvsem kemija vode) in projekt, je bilo med projektiranjem treba vzpostaviti primerne kriterije, in sicer:

a/ Termohidravlični vidiki
- izogniti se gretju špranj,
- izogniti se zastajanju pretoka,
- izogniti se koncentraciji nečistoč.

b/ Mehanski vidiki
- zmanjšati zaostale napetosti v ceveh,
- zmanjšati vibracije cevi.

c/ Vidiki obratovanja/vzdrževanja
- zagotoviti zadostno rezervo površine za prenos toplote, ki bi se med obratovanjem lahko zmanjšala zaradi čepljenja cevi in usedlin na ceveh,
- zmanjšati delež kapljevine v pari,
- zmanjšati toplotne obremenitve na priključku cevovoda napajalne vode na tlačno mejo (lupino),
- zagotoviti ustrezen dostop osebja za preglede in vzdrževanja.

Da bi izpolnili zelo stroge zahteve nabavne specifikacije, je bilo izvedenih veliko predkvalifikacijskih in kvalifikacijskih testiranj pred uporabo določene tehnologije ali postopkov. Pomembnejše kvalifikacije so bile: kvalifikacija cevi U pred izdelavo, kvalifikacija vrtanja cevne stene, ekspanzije cevi v cevno steno, varjenja, oblaganj z nikljem in drugo, ki se nanašajo na kakovost čiščenja ter kakovost površine.

Zastopniki JE Krško so bili navzoči na različnih lokacijah ves čas izdelave uparjalnikov. Izdelavo in testiranje novih uparjalnikov so neodvisno preverjale tudi slovenske pooblaščene organizacije, npr.: Fakulteta za strojništvo, Inštitut za metalne konstrukcije, Inštitut za kovinske materiale in tehnologije in Inštitut za varjenje.

1 PROJEKTNA ZASNOVA

Nova uparjalnika sta projektirana v skladu s projektnimi kriteriji podjetja Siemens KWU. V naslednjih poglavjih je opisana projektna zasnova novih uparjalnikov za JE Krško (sl. 1).

Pressure Vessel Code Section III, Division 1, Subsection NB, Class 1 Components. Class 1 components are those which form the reactor coolant pressure boundary.

It is necessary to replace worn out steam generators because of the many degraded tubes and the high cost of maintenance. In the design and manufacture of the new steam generators a lot of changes were anticipated which would ensure better resistance to degradation. Because degradation mechanisms are mainly influenced by: materials, enviroment (water chemistry) and design it was necessary in the design phase to establish the following adequate criteria:

a/ Thermal-Hydraulic Aspects:
- Avoid heated crevices,
- Avoid flow stagnation zone,
- Avoid concentration of impurities.

b/ Mechanical Aspects:
- Minimize residual stresses in the tubes,
- Minimize tube vibrations.

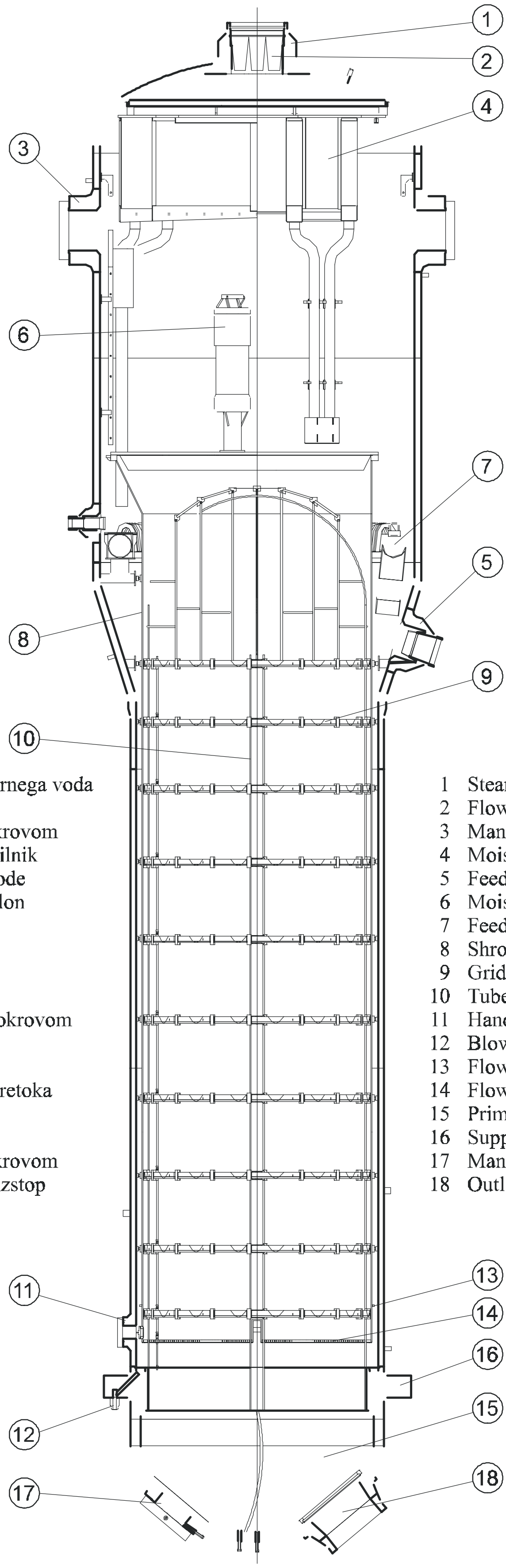
c/ Operational/Maintenance Aspects:
- Provide sufficient margin of heat transfer area, which can be used during operation to compensate for tube plugging and tube fouling,
- Minimize moisture carryover,
- Minimize thermal loading on the feedwater nozzle and pressure boundary,
- Provide adequate access for people during inspection and maintenance.

To fulfill the very stringent requirements of the procurement specification, numerous prequalification/qualification tests were done before a particular technology or operation was applied. The most important qualifications were: preproduction qualification of U-tubes, drilling qualification of tube sheet, expansion of tube inside the tube sheet, welding qualifications, nickel coating qualification and others related to cleaning or surface quality.

At every stage of manufacturing, NE Krško representatives were present at different locations. Additionally, manufacturing and testing of the new steam generators was independently checked by Slovenian Authorized Inspection Agencies, including: the Faculty for Mechanical Engineering, the Institute for Metal Structures, the Institute of Metals and Technology and the Welding Institute.

1 DESIGN CONCEPT

The new steam generators are designed in accordance with the Siemens KWU design concept. The following sections describe the design concept of the new steam generators (NSG) for the Krško Nuclear Power Plant (Figure 1).



1 Priključek glavnega parnega voda
2 Omejilnik pretoka
3 Vstopna odprtina s pokrovom
4 Izločevalnik vlage, sušilnik
5 Priključek napajalne vode
6 Izločevalnik vlage, ciklon
7 Napajalni prstan
8 Notranji plašč
9 Rešetka
10 Cevni snop
11 Pregledna odprtina s pokrovom
12 Drenažni priključek
13 Omejilnik pretoka
14 Plošča za usmerjanje pretoka
15 Primarna komora
16 Podporni obroč
17 Vstopna odprtina s pokrovom
18 Priključek za vstop in izstop reaktorskega hladila

1 Steam outlet nozzle
2 Flowlimiter
3 Manway with cover
4 Moisture separator, dryer
5 Feedwater nozzle
6 Moisture separator, cyclone
7 Feedwater ring
8 Shroud
9 Grid
10 Tube bundle
11 Handhole with cover
12 Blowdown nozzle
13 Flow restrictor
14 Flow distribution plate
15 Primary plenum
16 Support ring
17 Manway with cover
18 Outlet and inlet nozzle

Sl. 1. *Novi uparjanik za JE Krško*
Fig. 1. *New Steam Generator for Krško NPP*

1.1 Tlačne meje na primarni in sekundarni strani

Stene tlačne posode so narejene iz finozrnatih odkovkov iz nizko legiranega jekla (SA 508 CL 3a). Primarno stran sestavljajo primarna komora, valjasti obroč in cevna stena. Ukrivljena plošča iz zlitine Inconel 690TT (SB 168 UNS N06690), ki je privarjena na primarno glavo, valjasti obroč in spodnjo stran cevne stene, ločuje vstopni in izstopni prostor primarne komore. Vstopne in izstopne šobe imajo privarjene avstenitne konce, ki zagotavljajo ustrezen prehod med feritnimi šobami uparjalnika in avstenitnimi cevovodi za reaktorsko hladilo. Znotraj primarne komore sta na področju vstopne in izstopne šobe na nerjavno oblogo primarne komore privarjeni prirobnici za vgradnjo tesnilnih pokrovov. V vsakem od obeh delov primarne komore je vgrajen tudi avstenitni drenažni priključek.

Primarna stran cevne stene je oplaščena z večplastno oblogo iz nikljeve zlitine. Oba dela primarne komore, vključno z notranjimi površinami šob in valjastim obročem, sta v celoti oplaščena z najmanj dvema plastema avstenitnega jekla. Cevna stena skupaj s cevnim snopom ločuje primarni del uparjalnika od sekundarnega, kakor je razvidno s slike 1.

Tlačno mejo sekundarnega hladila sestavljajo: valjasta plašča v spodnjem delu, stožčasti prehod z valjastima koncema, valjasta plašča v zgornjem delu in torisferična glava s šobo za izstop pare na vrhu, ki je opremljena z omejilnikom pretoka. Valjasti plašč, privarjen na cevno steno, ima štiri pregledne odprtine – med njimi je kot 90°. Dve sta usmerjeni v smeri prostora med snopoma cevi. Krožni žleb na obrobju sekundarne strani cevne stene omogoča z obema šobama, privarjenima na spodnjo stran podpornega obroča cevne stene, zelo učinkovito drenažo.

Dva nastavka za zgornji podporni sistem uparjalnika sta privarjena na valjasti podaljšek stožca. Šoba glavne napajalne vode je privarjena na stožčasti prehod. Dve sekundarni vstopni odprtini sta na zgornjem valjastem plašču. Priključek pomožne napajalne vode in priključek za mokro shranjevanje sta privarjena na valjasti plašč nad stožcem. Priključek za mokro shranjevanje je med obratovanjem stalno zaprt s čepom.

1.2 Cevi uparjalnika

Cevi novih uparjalnikov so izdelane iz materiala Inconel 690 TT (UNS N06690), ki so ga razvili za čim boljšo odpornost proti napetostno korozijskim razpokam in proti splošni koroziji v vodi v visokotemperaturnih razmerah uparjalnika.

Inconel 690 je zlitina niklja z zmanjšanim deležem niklja (≥ 58 utežnih odstotkov) in večjim deležem kroma (27 do 31 utežnih odstotkov) v

1.1 Primary- and Secondary-Side Pressure Boundaries

The pressure-vessel walls are made of forgings of fine-grained low-alloyed ferritic steel (SA 508 CL 3a). The primary side consists of the primary head, the cylindrical ring and the tubesheet. A bent plate made of Inconel Alloy 690TT (SB 168 UNS N06690) welded to the primary head, the cylindrical ring and the underside of the tubesheet separates the two chambers of the head. The inlet and outlet nozzles are provided with austenitic safe ends to have a suitable transition between the ferritic nozzles and the austenitic reactor-coolant piping. Inside the primary head, in the area of the inlet and outlet nozzle, each flange ring for the installation of the nozzle dams is welded to the cladding. For drainage, two austenitic drain nozzles are installed in each chamber.

The primary side of the tube sheet is clad with a multi-layer nickel-based cladding. Both chambers of the primary head, including the nozzle inside surfaces and the cylindrical ring, are clad all over with at least a two-layer austenitic cladding. The tubesheet separates the primary from the secondary side as shown in Figure 1.

The secondary side of the pressure boundary consists of: two cylindrical shells in the lower section; the conical transition with cylindrical ends; two cylindrical shells in the upper section and the torispherical head with the integrated steam outlet nozzle on the top, which is equipped with a flow limiter. The cylindrical shell welded to the tube sheet is equipped with four handholes located 90° apart. Two of them are placed in the direction of the tube lane. A circular groove on the periphery of the secondary side of the tube sheet gives, together with the two nozzles welded to the underside of the tubesheet's support ledge, the possibility of a highly efficient blowdown.

The two trunnions for the SG upper support are welded to the lower cylindrical extension of the cone. The main feedwater nozzle is welded to the conical transition. The two secondary manways are welded to the upper cylindrical shell. The auxiliary feedwater nozzle and the wet lay-up nozzle are welded to the cylindrical shell above the cone. The wet lay-up nozzle is closed permanently with a cap during operation.

1.2 Steam Generator Tubes

The NSG tubing is made from Alloy 690 TT (UNS N06690). Alloy 690 TT was developed to resist SCC and general corrosion in the high-temperature aqueous environments associated with nuclear steam generators.

Alloy 690 is a nickel-based alloy with a reduced Ni content (≥ 58 wt%) and a higher Cr content (27 to 31 wt%) compared with Alloy 600.

primerjavi z zlitino 600. V Siemensovi specifikaciji cevi je najnižji delež kroma povečan na ≥ 28,5 utežnih enot, kar povečuje njeno odpornost na medkristalno napetostno korozijo in razjedanje. Delež niklja je od 59,0 do 62,0 utežnih odstotkov. Delež bakra, kobalta, dušika, bora in molibdena je omejen.

Mehanske lastnosti materialov, dobljene s testiranji, so naslednje:

R_{p02} (RT) 276 do 370 MPa (meja plastičnosti pri sobni temperaturi)
Rm (RT) ≥ 586 MPa (natezna trdnost pri sobni temperaturi)
R_{p02} (350°C) ≥ 243 MPa (meja plastičnosti pri 350°C)
Rm (350°C) ≥ 552 MPa (natezna trdnost pri 350°C)

1.3 Spoj cev – cevna stena

Spoj cev – cevna stena je izveden v štirih korakih:

1. uvaljanje koncev cevi zaradi učvrstitve cevi v cevno steno pred varjenjem,
2. varjenje cev – cevna stena,
3. hidravlično raztezanje cevi po celotni višini cevne stene,
4. mehanska razširitev cevi ob obeh koncih hidravlično razširjenega področja.

Uvaljanje

Med uvaljanjem cev namestijo v izvrtino cevne stene in uvaljajo na razdalji približno 20 mm. Tako zaprejo režo med cevjo in izvrtino. Optimalne varilne razmere dosežejo s primernim, vrtilnim momentom stroja za uvaljanje, ki je nastavljen tako, da se med nadaljnjim delom cev ne more premakniti. Material cevi se pri tem relativno malo preoblikuje, kar pomeni sorazmerno malo zaostalih napetosti.

Varjenje cev – cevna stena

Pri varjenju cev – cevna stena se uporablja avtomatski proces varjenja ozkega zvarnega roba s kovinskim polnilom. Varilnik se namesti z uporabo centrirne naprave. To in natančna priprava varjenja z valjanjem in strojno obdelavo zvarnega roba zagotavljajo enotno geometrijsko obliko zvarov. Neprepustnost spoja so preverili s helijevim testom prepustnosti.

Hidravlična razširitev

Hidravlična razširitev cevi po celotni višini cevne stene je izvedena z vodnim tlakom. Hidravlični sistem je bil elektronsko nadzorovan. Oblika orodja s tesnili na obeh straneh omogoča gladek prehod med razširjenim in nerazširjenim delom cevi.

In the Siemens KWU material specifcation for the tubes the minimum Cr content is increased to ≥ 28.5 wt% to improve the resistance against intergranular stress corrosion and pitting. The Ni content is specified as 59.0 to 62.0 wt%. The content of Cu, Co, N, B and Mo has also been restricted.

The mechanical values according to the material test sheet were:

R_{p02} (RT) 276 to 370 MPa (Yield strength at room temperature)
Rm (RT) ≥ 586 MPa (Tensile stress at room temperature)
R_{p02} (350°C) ≥ 243 MPa (Yield strength at 350°C)
Rm (350°C) ≥ 552 MPa (Tensile stress at 350°C)

1.3 Tube-to-Tubesheet Joint

The tube-to-tubesheet joint is made in the following four steps:

1. Tack rolling of the tube ends to position and fix the tubes in the tubesheet in preparation for welding.
2. Tube-to-tubesheet welding.
3. Hydraulic expansion of the tube over the entire height of the tubesheet.
4. Local mechanical expansion at both ends of the hydraulic expanded region.

Tack Rolling

During tack rolling the tube ends are positioned in the tubesheet hole and expanded slightly over a length of approximately 20 mm. This eliminates the gap between the tube and hole. To achieve optimum welding conditions the torque of the expansion tool is adjusted in such a way that the tube will not be dislocated during the subsequent work steps. The tube material receives a relatively low transformation and therefore relatively low residual stresses.

Tube-to-Tubesheet Welding

The tube-to-tubesheet welding utilizes an automatic welding process applying a single-pass pulsed gas tungsten arc (GTA) weld with filler metal. The welding gun was positioned by means of a centering device. This, together with the precise weld preparation by tack rolling and machining of the chamfer, ensures a uniform weld geometry. The leak-tightness of the joint was verified by a helium leak test.

Hydraulic Expansion

Hydraulic expansion of the tubes over the full height of the tubesheet was performed by hydroswaging. The hydraulic system was electronically controlled. The design of the mandrel with the seals at both ends ensures smooth transitions from the expanded to the unexpanded tube area.

Lokalna mehanska razširitev

Da bi lahko trdno pritrdili cevi na cevno steno in v celoti zatesnili špranjo na sekundarni strani, se cevi mehansko razširijo na obeh koncih hidravlično razširjenega področja. Dolžina razširitve na vsaki strani je 50 mm.

1.4 Podporni sistem cevnega snopa

Sistem cevnih podpor sestavljajo trije osnovni elementi: rešetkaste podpore ravnega dela cevi (sl. 2), vodoravni in navpični trakovi v loku cevnega snopa (sl. 3) in valoviti trakovi, ki so na vrhu cevnih lokov.

Projektiranje cevnih podpor izpolnjuje osnovne zahteve:

- izdelavo z zelo majhnimi tolerancami,
- zagotovitev preproste vgradnje cevi,
- prenašanje obremenitev med izdelavo, prevozom in vgradnjo,
- prenašanje obremenitev zaradi normalnega obratovanja in nezgodnih situacij, posebej tistih, ki nastanejo zaradi:
  - vibracij med stabilnim obratovanjem in prehodnimi pojavi, ki so posledica povečanega pretoka pare,
  - deformacij zaradi toplotnih in tlačnih obremenitev,
  - pospeškov zaradi naravnih tveganj in nezgod, ki jih povzroči človeški dejavnik,
- zmanjšanje tlačnih izgub, kar prispeva k večji recirkulaciji pare,
- zmanjšanje nalaganja usedlin na cevnih podporah,
- povečanje odpornosti cevi in njihovih elementov na korozijo, obrabo zaradi trenja in na utrujenost materiala,
- preprečenje stiskanja cevi zaradi oblog v špranjah.

Vsak izmed novih uparjalnikov je opremljen z 10 rešetkami (sl. 2), ki so približno enakomerno razporejene po ravni dolžini cevi med cevno steno in cevnimi zavoji.

Pri lokih cevi U je bilo še posebej treba paziti na:

- zagotovitev trdnosti sestave, ki je praktično brez zračnosti med cevmi in podpornimi trakovi (gibanje cevi je blokirano),
- valoviti trakovi postavijo loke v navpično smer in tako vzdržujejo stalno razdaljo med sosednjimi cevmi.

1.5 Rešetke

Rešetko (sl. 2) sestavljata dve vrsti trakov iz nerjavnega jekla, ki so na robu vpeti v notranji obroč. Kot med trakovi je 60°, vsake cevi pa se dotikajo štirje trakovi. Robovi trakov so vpeti v zarezanem notranjem obroču iz nerjavnega jekla, ki je vpet v zunanji okvir iz feritnega jekla. Vsak osmi

Local Mechanical Expansion

To fasten the tubes firmly to the tubesheet and to completely seal the gap on the secondary side the tubes are locally mechanically expanded at both ends of the hydraulically expanded area. The length of this expansion was 50 mm at each end.

1.4 Tube Bundle Support System

The tube support system consists of three basic elements which are the egg-crate-type supports in the straight run of the tubes (Fig. 2), the horizontal and vertical strips in the bend portion of the tube bundle (Fig. 3) and the corrugated strips which are located in the apex of the tube bends.

The design of the tube supports (grids) fulfils the basic requirements to:

- facilitate manufacture with very tight tolerances,
- ensure ease of tube insertion,
- accommodate all loads imposed during manufacture, shipment and installation,
- accommodate all operational and accident-induced loads, especially those due to:
  - steady-state and transient flow-induced vibration,
  - thermal and pressure-induced expansion,
  - accelerations due to natural and extemal manmade hazards,
- minimize flow pressure losses (contribute to high circulation ratio),
- minimize accumulation of crud deposits on the tube supports,
- maximize resistance of tubes and their supporting elements against corrosion, fretting and fatigue,
- avoid denting.

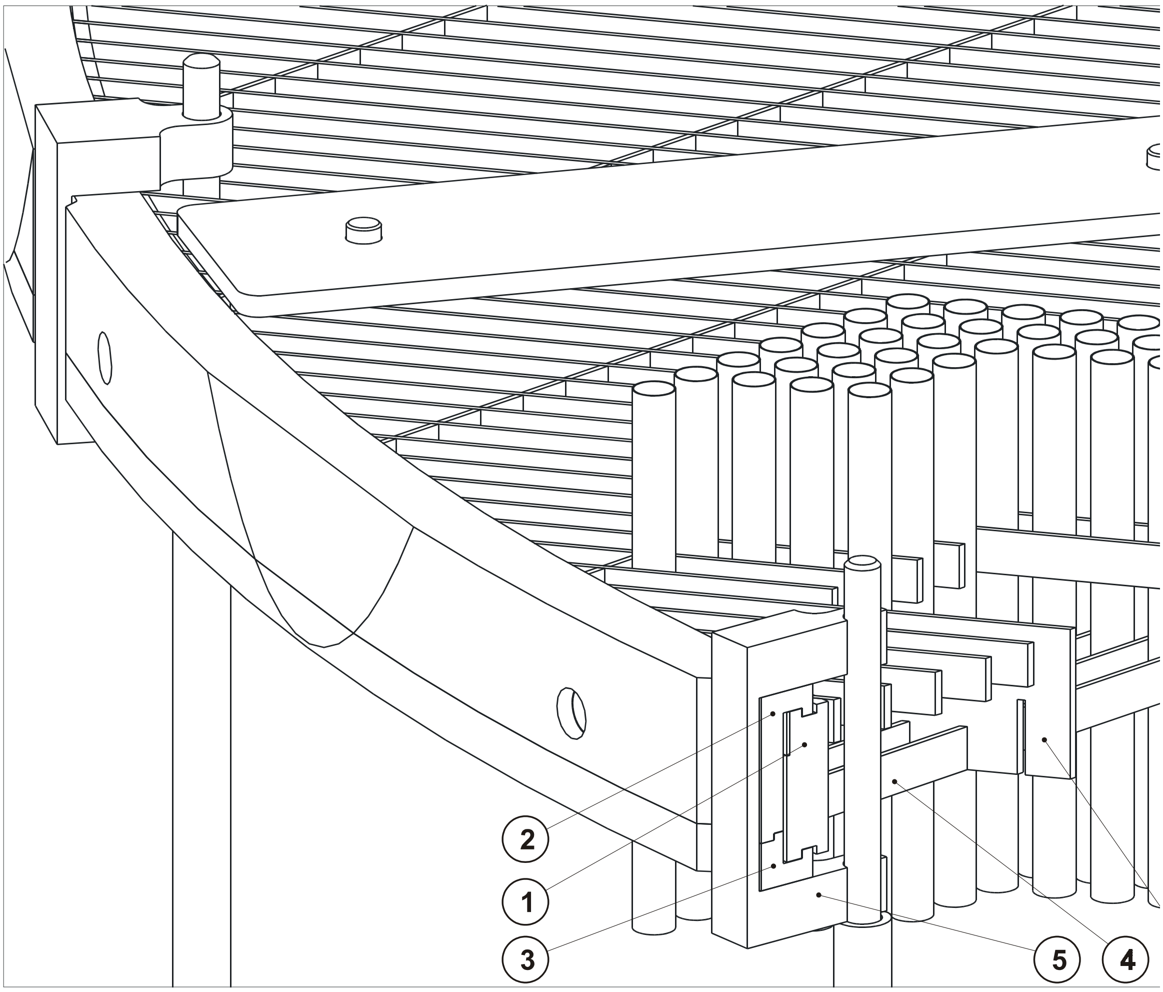
Each NSG is equipped with 10 full grids which are appoximately equally distributed over the straight tube length between the tube sheet and U-bend.

For the U-bend the following requirements have also to be taken care of:

- ensuring a compact assembly with nearly no clearances between the tubes and support strips block-type tubing).
- corrugated strips locate the U-bends in their vertical direction, thereby preventing contacts between tubes.

1.5 Egg-crate-Type Supports (Grids)

The egg-crate-type grid (Fig. 2) consists of two rows of stainless steel strips standing on edge and set at 60° to each other; four strips hold the tubes. The ends of the strips are engaged in a slotted stainless steel inner ring, which is engaged in an outer frame of ferritic material. Every eighth strip in the grid consists of a higher



1 – notranji obroč
2 – zgornji okvir
3 – spodnji okvir
4 – nižji trak
5 – spona
6 – višji trak

1 – inner ring
2 – upper frame
3 – bottom frame
4 – low bar
5 – spacer
6 – high bar

Sl. 2. *Podporna rešetka*
Fig. 2. *Egg-crate-type support (grid)*

trak v rešetki je višji podporni trak (69,5 x 3 mm) iz nerjavnega jekla, ki povezuje sicer po višini razmaknjene nižje trakove. Visoki podporni trakovi so vpeti z zarezami, speti med sabo, kar omogoča trdnost podpore v vodoravni smeri. Dve vrsti nižjih trakov (20 x 3,0 mm) sta vstavljeni v zareze ob zgornjih in spodnjih robovih višjih podpornih trakov. Med obročem iz nerjavnega jekla in feritnim zunanjim okvirom je zaradi različnega toplotnega raztezanja načrtovana ustrezna zračnost.

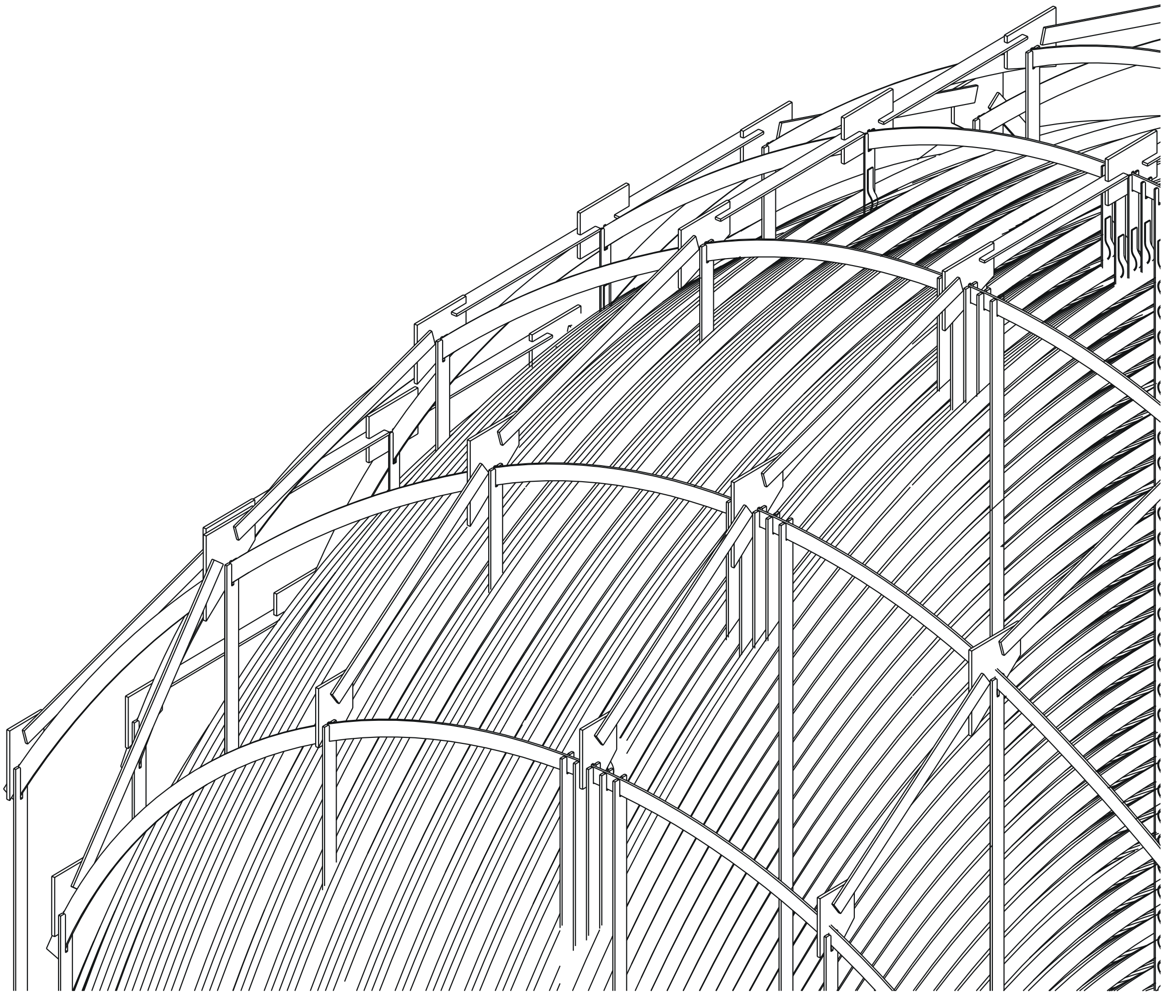
Oblika rešetk in podpor cevnih lokov onemogočajo ohlapnost in medsebojno premikanje trakov. Vse vijačne zveze so zavarovane s podložkami ali zavarjene.

Togost rešetke povečujeta avstenitni palici, ki sta nameščeni na zgornji in spodnji strani rešetke, ki se v prostoru med cevmi raztezata prek celotne rešetke. Palici sta privarjeni in pomenita

support strip (69.5 x 3 mm) also made of stainless steel and spanning the height of both low strip rows. The high-support strips are engaged into each other at the slotted points of the intersection, thus providing structural rigidity in the horizontal direction. The two rows of low-strips (20 x 3,0 mm) engage in slots along the top and bottom edges of the high support strips. To accommodate differential thermal expansion, suitable clearance is provided at the interface between the stainless steel ring and the ferritic frame.

The design of the egg-crate-type supports and the tube bend supports makes it impossible for the strips to work loose or move out of position. All screwed connections in the tube-support system are secured either by lock washers or by lock welds.

Additional stiffness is provided for the grid by two austenitic bars on the top and bottom side of the grid, which stretch over the grid diameter at the tube lane loca-



Sl. 3. *Podpore lokov cevi*
Fig. 3. *U-bend tube supports*

tudi oviro za tok v prostoru med cevmi (zmanjšan obvodni tok).

1.6 Podpora cevnih lokov

V področju snopa cevnih lokov je nameščena podporna struktura iz avstenitnega nerjavnega jekla (sl. 3), ki cevi podpira na optimalnih lokacijah. Podporne lokacije so določene na podlagi konzervativnih projektnih študij vibracij, rezultatov testiranj in odličnih obratovalnih izkušenj.

Podpora cevnih lokov je narejena iz trakov, neodvisnih med sabo, to so:

- navpični valoviti trakovi na vrhu cevnega zavoja,
- navpični ravni trakovi na obeh straneh valovitih trakov,
- vodoravni ravni trakovi na obeh straneh valovitih trakov.

tion. Welded pins connect the bars tightly. In addition, these bars form the tube lane block (reduced bypass flow).

1.6 Tube-Bend Support

In the U-bend region of the tube bundle an austenitic stainless steel support structure (Fig. 3) is used to support the tube bends at optimally spaced locations. The support locations are established in a conservative way after consideration of vibration design studies, experimental results and excellent operational experiences.

The tube-bend support is made up of independent strip elements, namely:

- Vertical corrugated strips located at the apex of tube bend,
- Vertical flat strips located at both sides of the corrugated strips,
- Horizontal flat strips located at both sides of the corrugated strips.

1.7 Razdelilni sistem glavne napajalne vode

Razdelilni sistem glavne napajalne vode v novih uparjalnikih sestavljajo: šoba glavne napajalne vode s toplotnim tulcem, cevovodi z razteznim elementom in razpršilnik napajalne vode.

Razdelilni sistem glavne napajalne vode izpolnjuje vse toplotne in hidravlične zahteve glede: majhnih toplotnih napetosti, onemogočanja razplastitve toka tekočine, enakomerne porazdelitve pretoka v povratnem kanalu in preprečevanja vodnega udara.

1.8 Sistem pomožne napajalne vode

Poleg sistema glavne napajalne vode je uparjalnik opremljen tudi s pomožnim sistemom napajalne vode. Pomožna napajalna voda teče skozi šobo pomožne napajalne vode do prhe, ki je projektirana kot površinski kondenzator. V prhi se voda intenzivno meša s prihajajočo paro. Toplota pare poveča temperaturo napajalne vode in tako bistveno omili toplotne udare tlačne meje in notranjih delov uparjalnika.

1.9 Razdelilnik pretoka

Namen razdelilnika pretoka (sl. 4) je povečati pretok kapljevine in zmanjšati parne praznine med cevmi nad cevno steno. S tem zmanjšamo odlaganje in zbiranje gošče. Sistem razdelilnika pretoka je sestavljen iz dveh plošč z izrezano odprtino.

1.10 Sistem izločevanja vlage

Siemensov sistem izločevanja vlage sestavljajo prvostopenjski in drugostopenjski izločevalniki vlage.

Ta sistem so razvili in testirali v različnih obratovalnih razmerah. Testiranja s paro in vodo so določila podatke o izločevanju vlage, to so: prenos kapljic, tlačne izgube in prenos kapljic pri različnih tlakih pare, nivojih vode in pretokih pare ter napajalne vode. Prvostopenjski izločevalniki (sistem: Siemensovi cikloni) so projektirani tako, da izločijo čim več vode iz mokre pare, ki zapušča cevni snop. Uparjalnik ima 48 prvostopenjskih izločevalnikov.

Drugostopenjski izločevalniki so privarjeni na torisferično glavo in imajo štiri privarjene podporne okvire za valovito pločevino (sistem: Peerless). Drenažne cevi na dnu vsakega izmed podpornih okvirov usmerijo izločene vodne kapljice na dno vodnih pasti. Te vodne pasti pari preprečijo, da bi jo odpihnilo navzgor proti drenaži, kadar nivo vode pade pod dno drenaž. Velikost drenažnih cevi je projektirana tako, da odvajajo vodo, ne da bi zmanjšale učinkovitost sušilnikov.

1.7 Main Feedwater Distribution System

The design of the NSG internal feedwater distribution system consists of the feedwater nozzle with thermal sleeve, piping with expansion bellows and a feedwater sparger.

The main feedwater distribution system fulfills all thermal and hydraulic requirements with respect to: low thermal stresses, destratification effect, equal flow distribution into downcomer and water hammer prevention.

1.8 Auxiliary Feedwater System

In addition to the main feedwater system the steam generator is equipped with an auxiliary feedwater system. The auxiliary feedwater is fed via the auxiliary feedwater nozzle to the auxiliary feedwater distributor, designed as a surface condenser. In the distributor the water is mixed intensively with the upcoming steam. The condensing heat of the steam increases the temperature of the feedwater and so thermal shocks of the pressure boundary as well as of the internals are prevented.

1.9 Flow-Distribution Plate

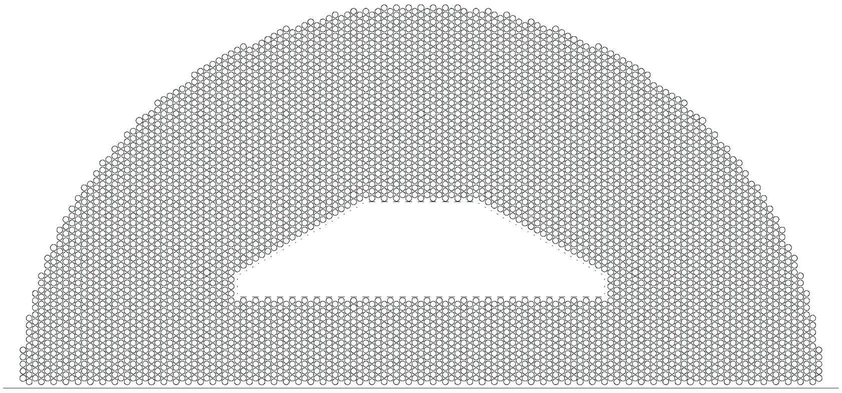
The purpose of the flow-distribution plate (Fig. 4) is to increase the liquid flow and to minimize steam voiding zones in the tubed region above the tubesheet so as to reduce sludge deposition or accumulation. The flow distribution baffle system consists of two orifice plates, each with an integrated cutout.

1.10 Moisture-Separation System

The Siemens KWU moisture separation system consists of first-stage separators and second-stage separators.

This system was developed and tested under a variety of operating conditions. The steam/water tests included obtaining separator performance data such as moisture carry-over, pressure loss and carry-under as a function of steam pressure, water level and steam and water mass flows. The first-stage separators (System: Siemens cyclones) are designed to separate as much water as possible out of the wet steam leaving the tube bundle. The steam generator accommodates 48 first stage separators.

The second-stage-separator assembly is welded to the torispherical head and consists of four welded support frames that accommodate the second-stage-separator plates (System: Peerless). Drain tubes in the bottom of each end of the support frames direct the separated water droplet downward into connected water traps. These water traps prevent steam from blowing up through the drains when the water level drops below the bottom of the drains. The drain tube sizes are designed to ensure that the water drains off without affecting drier efficiency.



Sl. 4. *Razdelilnik pretoka*
Fig. 4. *Flow-distribution plate*

V drugostopenjskih izločevalnikih je preostala vlaga v pari , ki zapušča prve izločevalnike, izločena do takšne mere, da iz uparjalnika do turbine potuje praktično suha para. Suhost pare na izstopu iz uparjalnika je najmanj 99,9 %, največji prenos vlage na izhodu omejilnika iztoka pare je 0,1 odstotek.

In the second stage separators the residual moisture in the steam leaving the first stage separators is removed to such an extent that almost dry steam flows from the steam generator to the turbine. The quality of extracted steam is 99.9%, the maximum moisture carry over is 0.1% at the outlet of the steam flow limiter.

1.11 Splošni podatki

1.11 General Data

UPARJALNIK STEAM GENERATOR	Stari D4 Old D4	Novi 72W New 72 W
toplotna moč thermalpower per SG	941MWt	1000 MWt
površina prenosa toplote heat transfer area	4487 m²	7177 m²
material cevi tube material	Inconel 600MA	Inconel 690TT
število cevi number of tubes	4578	5428
zunanji premer cevi outer diameter of tube	19,05 mm	19,05
tlak pare steam pressure	6,35 MPa	6,50 MPa
največja vlažnost max. steam moisture	0,25	0,10
obtočno razmerje circulation ratio	2,06	3,7
masa suhega uparjalnika total dry weight	330 t	345 t

2 IZDELAVA

Izdelava uparjalnikov je bila zelo zapletena naloga, ki so jo uspešno opravili v Španiji (ENSA). Konzorcij Siemens/Framatome je kot glavni izvajalec dobro vsklajeval dela s številnimi soizvajalci. Odkovki za tlačno mejo so bili izdelani na Japonskem (Japan Steel Works). Izdelava cevi U je potekala na Švedskem (Sandvik Steel). Glavne podkomponente: primarna glava, notranji plašč, zunanji plašč, rešetke, razdelilnik napajalne vode so bile izdelane v Italiji (ANSALDO). Tudi vijaki, matice, podaljšani tulci so bili izdelani v Italiji (OME). Iz Nemčije so dobili: primarne izločevalnike (Mechanic Center), tesnilne obroče

2 MANUFACTURING

Manufacturing of the steam generator was a very complex task which was very successfully completed in Spain (ENSA). Consortium Siemens-Framatome, as the main contractor, coordinated the numerous subsuppliers. The forgings for the pressure boundary were manufactured in Japan (Japan Steel Works). Manufacturing of the U-Tubes was performed in Sweden (Sandvik Steel). Major sub-assemblies such as: primary head, shroud, shell, grids, feedwater distribution, were manufactured in Italy (ANSALDO). Studs, nuts, extension sleeves were also manufactured in Italy (OME). Some parts came from Germany: primary separators (Mechanic Center), sealing discs (Kempchen) and

(Kempchen) in raztezne elemente (Witzenmann). Peerless izločevalniki (GSS Sarre Union) in material za pokrove (CLI) so iz Francije.

3 IZBOLJŠAVE

V primerjavi s sedanjima uparjalnikoma sta nova v zasnovi drugačna. Glavna razlika je vidna pri izbiri materialov, pri izdelavi in projektiranju.

a. Materiali
   Zlitina Inconel 690TT za cevi nadomesti zlitino Inconel 600MA.
   Material za tlačno mejo SA 508 CL.3a, prej SA 533 Gr.B.
b. Izdelava
   Odkovki, prej varjena pločevina (v novih uparjalnikih ni vzdolžnih zvarov).
   Natančnejša izdelava cevi.
   Vpetje cevi v cevno steno (minimizacija zaostalih napetosti).
   Kakovost površine obloge primarne glave (minimizacija obsevanosti osebja).
   Nikljeve obloge na omejilniku pretoka pare.
c. Projektne značilnosti
   Projekt cevnega snopa (bistveno povečana površina za prenos toplote, rešetke, učvrstitev proti vibracijam).
   Koncept napajanja z vodo (lega priključkov napajalne vode, razdelilni sistem napajalne vode).
   Valjasti obroč med cevno steno in primarno glavo.
   Povečani premer vstopnih odprtin.

4 SKLEP

Nova uparjalnika sta bila z ladjo pripeljana iz Santandra (Španija) do Kopra, iz Kopra v Krško pa brez težav s cestno-transportno kompozicijo. Spravljena sta v posebnem prostoru, kjer čakata na zamenjavo.

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expansion compensators (Witzenmann). Peerless separator vanes (GSS Sarre Union) and material for opening covers (CLI) came from France.

3 IMPROVEMENTS

The NSG is different from the existing steam generator. The essential differencies are visible in the chosen materials, manufacturing and design.

a. Materials
   Tubing material, alloy 690TT, replaced alloy 600MA
   Pressure boundary material, SA 508 Cl.3a, replaced SA 533
b. Manufacturing
   Forging vs. plate (no longitudinal welds in the new steam generators)
   More precise tube processing
   Expansion of tubes
   Quality of channel head cladding surface finish (Principle As Low As Reasonable Achievable, ALARA, for radiation exposure of personnel))
   Steam flow limiter nickel coating
c. Design features
   Tube bundle design (enlarged heat exchanger area, grids, AVB)
   Feedwater concept (position of feedwater nozzle, feedwater distribution system)
   Internals design (auxiliary feedwater, separators, shroud and deckplate)
   Cylindrical ring between tubesheet and channel head
   Manway opening diameter enlarged.

4 CONCLUSION

The new steam generators were transported from Santander (Spain) to Koper by ship and from Koper to Krško by truck without any damage. They are sited in the Krško storage area and are waiting to replace the existing generators.

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Projekt zamenjave uparjalnikov jedrske elektrarne Krško

Steam-Generators Replacement at the Krško Nuclear Power Plant

Janko Cerjak - Andrej Androjna - Bojan Volarič

V prispevku smo predstavili osnovne opravke pri projektu zamenjave uparjalnikov, ki obsegajo vse transportne in logistične dejavnosti kakor tudi vse trajne spremembe, potrebne zaradi prilagoditve novih uparjalnikov na sedanje sisteme in načrtovanega povečanja moči. Vse dejavnosti se izvajajo tako, da bodo doseženi osnovni nameni zamenjave:1. zagotoviti zamenjavo znotraj vseh pogodbenih obveznosti, 2. kolektivna doza izpod 1,4 Sv, 3. nobenih izgubljenih dni zaradi poškodb pri delu.

(Ključne besede: transport, sistemi dvižni, meritve optične, dekontaminacija)

The paper covers all the basic techniques of the steam-generator replacement (SGR) project including all rigging /handling and other logistical activities as well as all the permanent modifications required to adapt systems for the new steam generators and the corresponding power increase. All activities will be performed in a way which ensures that the following main project goals will be met: 1. all work will be done within contractual obligations; 2. collective dose below 1.4manSv; 3. zero lost working days due to personal injury.

(Keywords: transport, lifting systems, optical survey, decontamination)

0 UVOD

Jedrska elektrarna Krško je s Konzorcijem Siemens/Framatome februarja 1998 sklenila pogodbo o zamenjavi uparjalnikov, ki je eden izmed projektov modernizacije elektrarne. Članek obravnava različne vidike projekta: obseg, načrtovanje, inženiring, pripravo spreminjevalnih paketov za pridobitev dovoljenj, vodenje, pomembnejše uporabljene tehnike itn. in prikazuje dejavnosti, ki so načrtovane od aprila do junija 2000.

Projekt poteka po sistemu "ključ v roke", kar pomeni, da Konzorcij izvaja vsa inženirska dela, pripravlja dokumentacijo projektnih sprememb in izvaja dejavnosti na objektu. JE Krško pridobiva dovoljenja in skrbi za vse dejavnosti, ki zahtevajo sodelovanje elektrarne ali zadevajo preostale projekte posodobitve.

1 OBSEG PROJEKTA

1.1 Priprava in transport uparjalnikov

Ta paket obsega vse dejavnosti, ki so potrebne za pripravo in transport starih in novih

0 INTRODUCTION

The Krško nuclear power plant (NPP) awarded the contract for the Steam-Generator Replacement Project, which is one of the modernization projects at Krško, to the Consortium Siemens - Framatome in February 1998. This paper deals with the various aspects of the project: scope, planning, engineering, preparation of the modification packages for licensing, management, major techniques used, etc., showing also the status of the activities for the project which are scheduled to be performed in April - June 2000.

The project is being performed on a "turnkey" basis, which means the Consortium is performing all the engineering, preparation of the modification packages and site activities; Krško NPP is dealing with the licensing of the project and all the activities interfacing with the plant and other modernization projects.

1 PROJECT SCOPE

1.1 Steam-Generator Rigging and Handling

The rigging package comprises all the activities which are required for handling and transuparjalnikov med zunanjim odlagališčem v večnamenski stavbi in njunim prostorom v reaktorski zgradbi. Značilni podatki uparjalnikov so:

– dva stara uparjalnika, mase 321 ton, dolžine 20,65 m, največjega premera 4474 mm, je treba prepeljati iz reaktorske zgradbe do končnega odlagališča v večnamenski stavbi,
– dva nova uparjalnika, mase 337 ton, dolžine 20,85 m, največjega premera 4474 mm, je treba prepeljati iz začasnega skladišča v večnamenski stavbi v reaktorsko poslopje.

1.1.1 Postopek ravnanja in transporta

Transport uparjalnika zajema naslednje glavne korake (sl. 1):

– transport med večnamensko in reaktorsko zgradbo na višini 100 m
– dvigovanje med elevacijo 100 m in obratovalno ploščadjo – višna 115 m
– vodoraven premik v reaktorsko zgradbo in iz nje skozi odprtino za opremo na obratovalni ploščadi – višina 115 m
– dvigovanje iz obratovalne ploščadi – višine 115 do prostora uparjalnikov na višini 108 m

1.1.2 Oprema pri ravnanju in transportu

Sistemi, ki se uporabljajo za te naloge, temeljijo na posebej prilagojeni opremi - za dviganje težkega bremena. Sestavljajo jo naslednje glavne komponente:

Vozilo za težki tovor

Zunanji prevoz uparjalnikov poteka na samopogonskem 14-osnem vozilu. Izbrani sistem je za takšne transportne naloge značilen. Uporabili so ga že pri izvedenih zamenjavah uparjalnikov (Ringhals 3, Švedska).

Vozilo omogoča dviganje bremena z začasnega skladišča z vgrajeno hidravlično dvižno ploščadjo (Δh = +/-300 mm). Zato pri natovarjanju in raztovarjanju niso potrebna dodatna dvigala.

Zunanji dvižni sistem

Za dviganje uparjalnikov z višine 100 m na 115 je nameščen zunanji dvižni sistem, ki omogoča navpično dviganje in vodoravno obračanje bremena. Po prevzemu uparjalnika s transporterja v vodoravni legi, se uparjalnik dvigne, s štirimi 200-tonskimi hidravličnimi dvigali. Ko uparjalnik doseže obratovalno ploščad, višino 115 m, se s pomočjo drsnega sistema potisne do reaktorske zgradbe. Podporni okvir dvižnega sistema sestavljata dva stebra, dva nosilca (dolžine

portation of the old and new steam generators (SGs) between the outside storage location in the multi purpose building (MPB) and the SG cubicles in the reactor building (RB). The characteristic data of the steam generators are:

– two old SG, weight: 321 tons; length: 20,65 m; max. diameter: 4474 mm to be transported from RB to final storage in MPB.
– two new SG, weight: 337 tons; length: 20,85 m max. diameter: 4474 mm to be transported from temporary storage in MPB into the RB.

1.1.1 Rigging tasks

The SG transport consists of the following main steps (see figure 1):

– Ground transportation between MPB and RB on ground elevation (EL) 100 m
– SG lifting operation between EL 100 m and operation floor level EL 115 m
– SG horizontal transfer into and out of RB through equipment hatch on operation floor EL 115 m
– SG lifting from operation floor EL 115 into the SG housings on EL 108 m

1.1.2 Rigging Equipment

The systems employed for these tasks are mainly based on equipment used in heavy lifting, specially adapted for this purpose. The main components are:

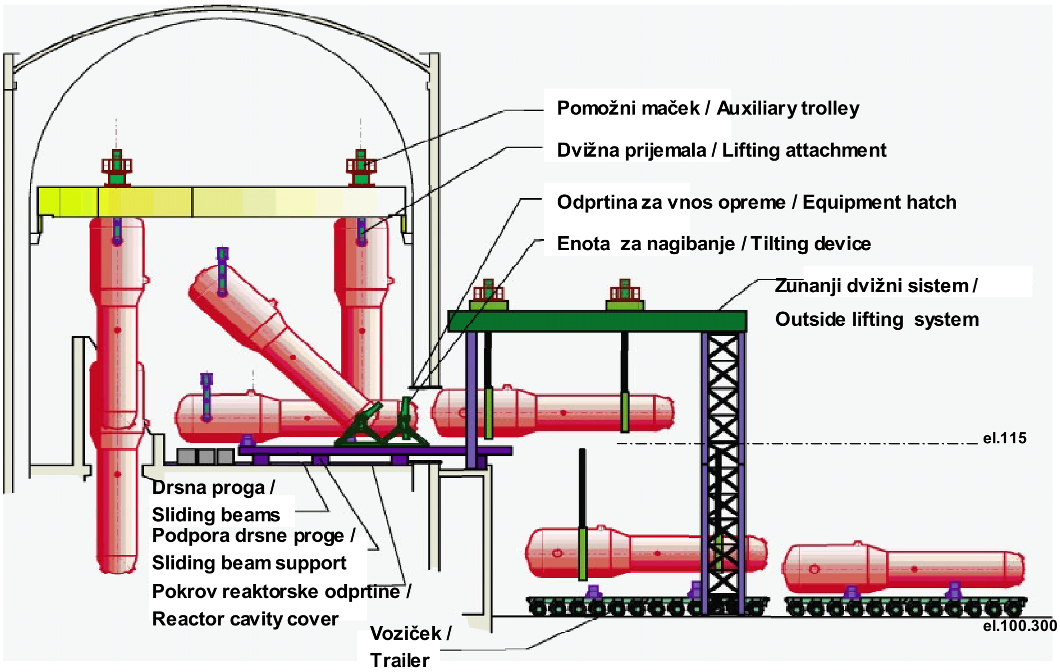
Heavy-load trailer

The ground transportation is performed by a self-propelled 14 axle heavy-load trailer. The chosen trailer is typical for this kind of transport task. The trailer to be used has already been employed for previous steam-generator replacements (Ringhals 3, Sweden).

The trailer allows the transfer of loads from storage supports with its integrated hydraulic lifting platform (Δh = +/-300mm). Therefore no additional cranes are required for loading and unloading of the trailer.

Outside Lifting System

For the SG lifting from ground level EL 100 m to operation floor level EL 115 m an outside lifting gantry is installed. The lifting system enables vertical hoisting and horizontal shifting of loads. After take-over of the steam generator from the transport trailer in the horizontal position the SG is lifted by 4 x 200 ton wire jacks. When the steam generator has reached the upper level, it is shifted towards the sliding system at EL 115 m on which the SG is moved into the RB. The support frame of the lifting system consists of two towers, two heavy



Sl. 1. *Ravnanje z uparjalnikom*
Fig.1. *Steam-generator rigging*

34 m) in nosilni okvir pred odprtino za vnos opreme. Stebra sta izdelana iz modularnih jeklenih elementov, nosilci in vhodni okvir pa kot standardni jekleni sestavi.

Vozička sta nameščena na nosilcih, vsak pa ima po dve 200-tonski hidravlični dvigali. Vodoravno premikanje vozičkov se doseže s pomočjo vodoravno nameščenih hidravličnih valjev, ki omogočajo vzporedno ali neodvisno premikanje obeh vozičkov.

Drsni sistem

Odprtina reaktorske stavbe za vnos opreme ima premer 6,95 m, kar zadošča za transport uparjalnika skoznjo.

Vodoraven premik uparjalnika skozi odprtino se izvede z drsnim sistemom, ki leži pod zunanjim dvižnim sistemom na višini 115 m. Nato se uparjalnik z dvema podporama namesti na drsni sistem: ena podpora je na strani priključka parnega voda ob drsnem sedlu in druga na strani primarne komore ob enoti za nagibanje.

Uparjalnik se potisne v reaktorsko stavbo s parno kupolo naprej. Znotraj reaktorske stavbe se ta postavi v pokončno lego z uporabo polarnega žerjava. Pri tem posegu deluje enota za nagibanje kot tečaj, ki dovoljuje nadzorovano dvigovanje uparjalnika ob hkratnem nagibanju.

Spremembe polarnega žerjava

Polarni žerjav v sedanji obliki ne zmore potrebne dvižne višine. Najvišja dvižna višina žerjava ne zadostuje, da bi se lahko pomaknil prek sten

load girders (lengths 34 m) and one portal frame in front of the equipment hatch. The towers are built from modular steel elements. The girders and the portal frame are fabricated as standard steel structures.

Two cross beams are installed on top of the girder, each equipped with two 200 ton hydraulic wire jacks. The horizontal sliding of the cross beams is achieved by horizontally installed wire jacks which allow moving both in parallel, or independently from each other.

Sliding System

The equipment hatch in the RB has a diameter of 6.95 m. This is sufficient to allow the SG transport into the RB through this opening.

The steam generator's horizontal transfer through the equipment hatch is performed by a sliding system resting below the outside lifting system at EL 115 m. The SG is carried by two supports when set onto the sliding system: one at the steam-dome side by a sliding saddle and at the channelhead side by the so-called tilting device.

The SG is moved into the RB with the steam dome entering first. When inside the RB the SG body is brought to the vertical position by means of the polar crane. For this operation the tilting device acts as a bearing to allow for controlled raising of the SG.

Polar-crane modifications

The polar crane in the existing configuration does not allow handling of the SG as required in terms of lifting height and trolley capacity. The maxiprostora uparjalnika s pričvrščenim uparjalnikom – potrebna bi bila obsežna gradbena dela v reaktorski zgradbi.

Zmogljivost polarnega žerjava je 320 ton, masa novega uparjalnika pa 337 ton. Obe omenjeni zahtevi sta rešeni z vgradnjo pomožne dvigovalne naprave na dvigalu. Ta nadomesti sedanjega mačka, ki ga umaknemo na skrajno točko mostu. Problem nezadostne dvižne višine je rešen z ustrezno obliko pomožne dvigalne naprave in optimalno dolžino plošč za pritrditev uparjalnika.

Nosilnost mostu polarnega žerjava je izboljšana z novo, lažjo dvigalno napravo in ugodno porazdelitvijo bremena. Dodatni preveritveni izračuni za vse obremenjene sestave potrjujejo sprejemljivost te rešitve. Polarni žerjav je s temi ukrepi zmožen premikati uparjalnik brez sprememb nosilnih delov.

Uparjalnik se dvigne s 400-tonskim hidravličnim dvigalom, podprtim z osnim ležajem, ki omogoča nagibanje visečega uparjalnika okoli njegove navpične osi. To je potrebno zaradi številnih kotnih prilagoditev uparjalnika med različnimi fazami vgradnje.

Hidravlične dvižne naprave

Hidravlične dvižne naprave uporabljamo za ravnanje s težkimi bremeni, npr. dvigovanje in vodoravne premike. Združujejo prednosti hidravličnih dvižnih naprav s prožnostjo kabelskih vitlov in zagotavljajo močne hidravlične sile z neomejenimi premiki. Premikajo se gladko in so zaradi svojega načina delovanja varni tudi v primeru okvare oz. odpovedi.

1.1.3 Posebne zahteve

Celoten postopek transporta in ravnanja z uparjalnikom je bil obdelan z vidika jedrskega in ekonomskega tveganja. Ker se večina aktivnosti zamenjave izvede po zaustavitvi elektrarne in brez gorivnih elementov v reaktorju, obravnavajo varnostna vrednotenja jedrskega tveganja predvsem zahtevo, da gorivo v bazenu za izrabljeno gorivo ne pomeni nevarnosti.

Tudi običajna ekonomska tveganja morajo biti minimalna. To pomeni, da morajo biti tudi sestave, ki niso v varnostnem razredu, dokazane kot varne. Presegati morajo torej običajne zahteve.

Pri sedanjih zamenjavah uparjalnikov so zunanji dvižni sistem praviloma postavili pred zaustavitvijo elektrarne. Tak postopek je v Krškem – glede na rezultate varnostnega vrednotenja – nemogoč. Ugotovljeno je, da bi namestitev zunanjega dvižnega sistema lahko vplivala na varnostne sisteme, kakor so zbiralnik vode za menjavo goriva, zbiralnik kondenzata in zbiralnik reaktorske dodajne vode.

mal lifting height of the crane trolley is not sufficient to cross the walls of the SG housings with the attached steam generator and would require extensive civil engineering works inside the RB.

The polar crane has an original capacity of 320 tons. But the weight of the new Steam Generator is 337 tons. These two deficiencies are remedied by the installation of a special auxiliary lifting gantry which provides the required properties. This gantry substitutes the existing trolley which is parked at one end of the bridge. The problem of insufficient lifting height is solved by a suitable design of the hoisting unit and the SG attachment plates with optimised length.

The load bearing capacity of the polar-crane bridge is improved by the new gantry's lightweight design and an advantageous load distribution. Additional verification calculations for all loaded structures prove this is an acceptable solution. With these measures the polar-crane bridge is capable of handling the SG load without structural modifications.

SG lifting is achieved by a 400 ton wire jack. This wire jack is supported by an axial bearing which allows rotation of the hanging steam generator about its vertical axis. This is necessary for the several angular adjustments of the SG during the different rigging phases.

Hydraulic Wire Jacks

Wire jacks are employed within the rigging package in several applications for the handling of heavy loads. Hoisting and horizontal shifting is powered by wire jacks. Wire jacks combine the advantages of hydraulic jacks with the flexibility of cable winches. They provide high hydraulic forces with an unlimited lifting stroke. The movements are smooth and they are fail safe under accident conditions due to their working principle.

1.1.3 Specific Requirements

The entire process of SG rigging and handling was investigated in view of nuclear and economic risk. As most of the SGR activities are performed after shutdown of the plant with an unloaded core, safety evaluations for nuclear risk deal mainly with the requirement that the fuel in the spent fuel pool is not a danger.

Conventional risks are also to be minimised. This means that structures which are not nuclear-safety related also have to be demonstrated as safe, above normal requirements.

According to a typical SG replacement schedule the outside lifting system is erected prior to the shut down of the plant. According to the results of the safety evaluation this is, in practise not possible at Krško. It was determined that the safety related systems RWST (Refuelling Water Storage Tank), CST (Condensate Tanks) and Reactor Makeup Water Storage Tank may be affected by the outside

Ker bi namestitev in ravnanje s težkimi bremeni v bližini omenjenih zbiralnikov lahko pomenila zmanjšanje varnosti elektrarne, mogoči nadomestni ukrepi pa niso na voljo, zgodnja postavitev zunanjega dvižnega sistema praktično ne pride v poštev. Torej je prestavljena na čas po zaustavitvi elektrarne.

Običajno razmeroma nepomembna dejavnost postavitve zunanjega dvižnega sistema lahko tako postane dejavnost na kritični poti projekta, ki vpliva na izvedbo celotnega projekta. Da bi kar najbolj zmanjšali možne negativne posledice, poteka zelo natančno načrtovanje vseh dejavnosti sestavljanja.

1.2 Dejavnosti na ceveh reaktorskega hladiva

1.2.1 Optične meritve, učvrstitve in prilagoditve

Delovni paket obravnava prilagoditev novih uparjalnikov na sedanji sistem reaktorskega hladila. Uparjalnik se odmakne od sistema reaktorskega hladila z rezanjem primarnih cevovodov ob priključkih na stara uparjalnika. Načrtovanje prilagoditev mora omogočiti natančno prilagoditev novega uparjalnika, upoštevaje odstopanja dimenzij in posebne zahteve za vzpostavitev prvotnega stanja. Te dejavnosti potekajo v tesni povezavi z optičnimi meritvami. Na podlagi zahtev za prilagoditev se rezultati optičnih meritev uporabijo

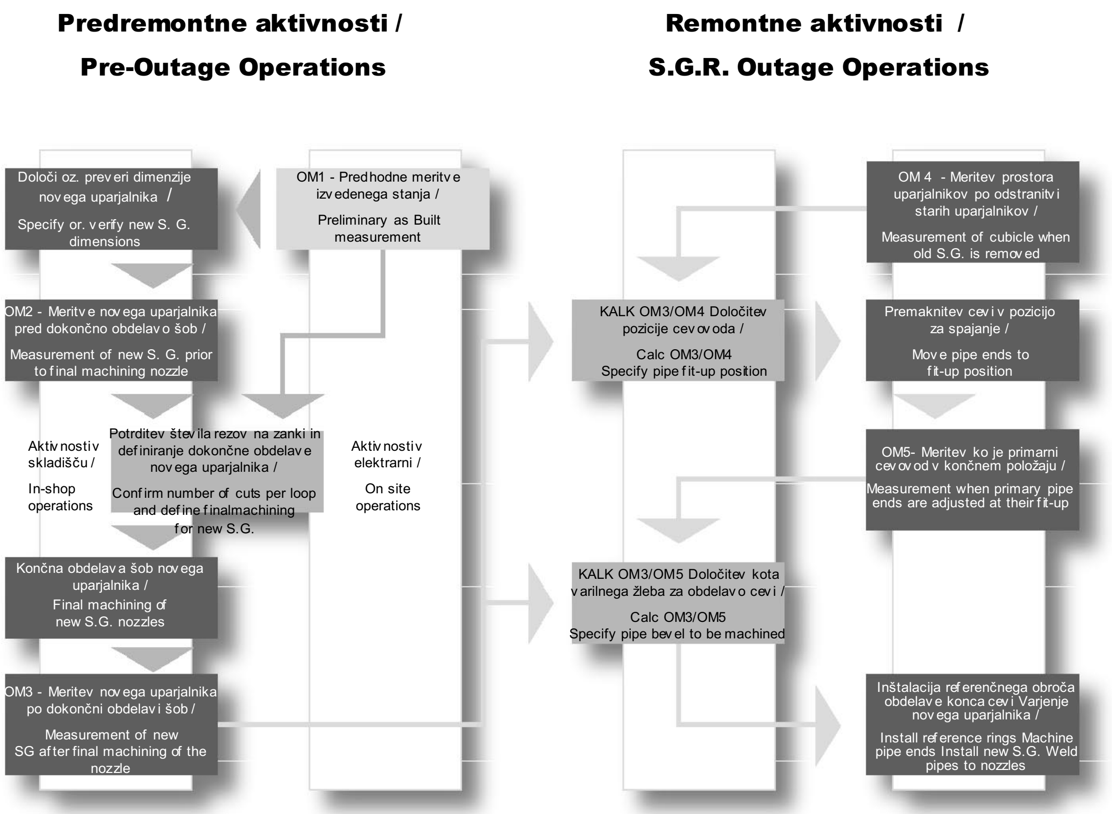
lifting system during its installation. As heavy-load rigging activities in the vicinity of these tanks would be a potential risk to the nuclear safety of the plant and feasible substitution measures are not available, the early erection of the lifting system is practically ruled out. Therefore, the erection activities have to be postponed until after the shut down.

The normally non-critical erection of the outside lifting system may become a critical activity with an impact on the overall project time schedule. To minimise the negative consequences as much as possible, very detailed planning of all erection activities is in progress.

1.2 Activities at the reactor coolant pipe

1.2.1 Optical survey, clamping and fit-up

This work package deals with the adaptation of the new steam generators to the existing reactor coolant system (RCS). The SG is separated from the remaining RCS by cuts at the primary nozzles. The fit-up engineering has to provide the basis for the accurate fit-up of the new SG, taking into account the dimensional deviations and the specific requirements of the restoration process. The fit-up activities are performed in close co-operation with the optical survey task. Based on fit-up requirements the optical measurement results are used to determine optimised fit-



Sl. 2. *Zaporedje optičnih meritev*
Fig.2. *Sequence of optical measurements*

za določitev optimalnih leg za nova uparjalnika. Da bi izpolnili te zahteve, obsega delovni paket naslednje naloge (sl. 2):

- natančno prilagoditev dimenzij novih uparjalnikov in sedanjega sistema reaktorskega hladiva,
- kompenzacijo krčenja novega zvara,
- določitev dovoljenih napetosti v sistemu reaktorskega hladila s preveritvenimi izračuni,
- dimenzijsko prilagoditev podpor uparjalnika.

Postopek prilagoditev pri zamenjavi uparjalnika z metodo dveh rezov zahteva merjenja v naslednjem zaporedju (OM = optične meritve):

- OM 1 izvedbene meritve sedanjega sistema reaktorskega hladiva,
- OM 2 meritve novih uparjalnikov pred pripravo zvarnega roba,
- OM 3 meritve novih uparjalnikov po pripravi zvarnega roba,
- OM 4 meritve cevnih koncev reaktorskega hladiva po rezanju v blokirani legi,
- OM 5 meritve cevnih koncev v legi namestitve pred obdelavo,
- OM 6 meritve po varjenju.

Uporabljena merilna tehnika

Osnovna tehnika za optične meritve je določitev koordinat prostorskih predmetnih točk z optičnim osredotočenjem in trikotnimi izračuni. Pri teh meritvah je uporabljen industrijski merilni sistem z elektronskimi teodoliti.

Merilni sistem sestavljajo elektronsko povezani teodoliti in prenosni računalnik s posebnim računalniškim programom. Med eno meritvijo ob zamenjavi uparjalnika se uporabijo skupno eden do štirje teodoliti. Vzporedno z izvajanjem meritev potekajo tudi preverjanja izračunov, da bi odkrili vprašljive rezultate. Ti se med samimi meritvami uporabljajo za preveritev ali popravke dobljenih podatkov.

Preverjanje podatkov poteka zunaj reaktorske zgradbe. Izračuni prilagajanj se izvajajo s posebnim programskim orodjem, ki je bilo uspešno uporabljeno že med do tedaj izvedenimi zamenjavami uparjalnikov.

1.2.2 Rezanje, brušenje, priprava zvarnega roba

Rezanje cevi sistema reaktorskega hladila se izvaja z uporabo mehanskega postopka.

To mehansko rezanje omogoča:

- rezanje cevi iz nerjavnega jekla (zunanjega premera do 1 m in debeline do 100 mm),
- rez z zunanje strani brez vstopa v primarno komoro starega uparjalnika,
- delo znotraj omejenega prostora okoli spoja med cevjo in šobo.

Rezalni stroj je vpet na cevi sistema reaktorskega hladila. Pogon je hidravličen. Rezanje se izvaja v dveh glavnih korakih:

up positions for the new steam generators. To fulfil these requirements the following tasks have to be considered in this work package (Figure 2):

- accurate dimensional adaptation of the new SG and existing RCS;
- compensation of the weld shrinkage of the new welds;
- determination of allowable stresses in the RCS by verification calculations;
- dimensional adaptation of SG supports.

The fit-up process within a 2-cut steam generator replacement requires the following measurement steps (OM = Optical Measurement):

- OM 1 as-built survey of the existing RCS,
- OM 2 survey of new SGs prior to weld-edge preparation,
- OM 3 survey of new SGs after weld-edge preparation,
- OM 4 survey of RC pipe ends after cutting in blocked position,
- OM 5 survey of RC pipe ends in fit-up position prior to machining,
- OM 6 survey after welding.

Applied measurement technique

The basic technique for the optical survey is the determination of 3-D coordinates of the object points by optical focusing and triangular calculations. For these measurements an industrial measurement system with electronic theodolites is used.

The measuring system consists of electronically combined theodolites and a notebook PC for data processing with specific measuring software. For SG replacement surveys, normally 1 to 4 theodolites are used together within one survey. In parallel with the taking of measurements, verification calculations are automatically performed to detect questionable results. These indications are used during the running measurement session, to verify or to correct the received measurement data.

The data evaluation is performed outside the RB. The fit-up calculations are performed with specific software tools which were successfully used in previous steam-generator replacements.

1.2.2 Cutting and beveling

The RCS pipe cutting is performed using a mechanical process.

This mechanical cutting allows:

- cutting of stainless steel pipes (external diameter up to 1m and thickness up to 100 mm);
- outside cut without entering the old SG channelhead;
- operation within the limited space around the pipe / nozzle junction.

The cutting machine is supported on the RCS pipe. A hydraulic power unit drives the machine. The RCS cutting is performed in two main steps:

– rezanje do 90 odstotkov debeline cevne stene; globina rezila se spremeni samodejno pri vsakem obratu,
– preden zunanja rezilna orodja prerežejo v notranjost cevi, se rezila zamenjajo z rezalnimi kolesi, ki odrežejo cev, ne da bi opilki padli v cev.

Zvarni rob cevi sistema reaktorskega hladiva se pripravi po dekontaminaciji in optičnih meritvah.

Rezkalni stroj se osredišči na cevi in namesti z obročem, ki se že prej nastavi z optičnimi merjenji. Kroglasti zgib in mehanske prižeme na stroju omogočajo natančne prilagoditve rezkalnega stroja glede sosrednosti in nivoja.

Po nastavitvi se rezkalni stroj uporablja z veliko natančnostjo za strojno obdelavo novega zvarnega roba na točno določenem mestu na cevi.

Geometrijska oblika zvarnega roba in njegova natančnost sta v skladu s postopkom argonskega varjenja v ozkem žlebu.

Ista oprema se bo uporabila pri pripravi zvarnega roba na priključkih novih uparjalnikov.

1.2.3 Dekontaminacija

Namen tega postopka, prikazanega na sliki 3, je zmanjšati sevalne doze v področju cevnih

– Using blade cutters, up to 90% of the pipe wall is cut. The re-indexing of the blade cutter depth is achieved automatically after each rotation
– Before the external cutting tools break through the interior of the pipe, the blade cutters are replaced by cutting wheels, which separate the pipe from the old SG without introducing debris into the pipe.

The RCS pipe beveling is performed after decontamination and an optical survey.

The beveling machine is centered in the pipe and adjusted with the reference ring previously set by the optical survey. A spherical ball joint and mechanical jacks installed on the machine allow a fine adjustment of the beveling machine in concentricity and planeity.

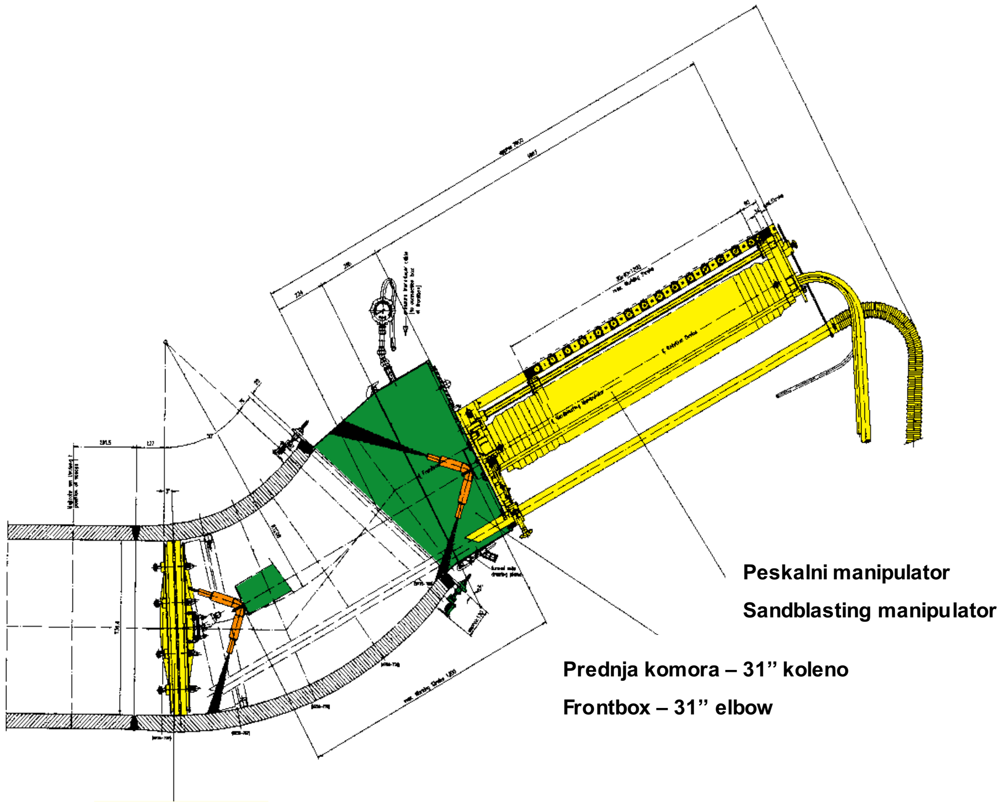
Once adjusted, the beveling machine is used for machining the new bevel, with a great accuracy, at its exact position on the pipe .

The bevel geometry and its accuracy are in accordance with the gas tungsten arc welding (GTAW) narrow-gap process.

The same equipment will be used to perform the bevel on the new SG nozzles.

1.2.3 Decontamination

The purpose of this decontamination shown in Fig.3 is to reduce the radiation dose in the area of



Sl. 3. *RC-L dekontaminacija konca cevi: oprema za dekontaminacijo / vroči krak*
Fig.3. *RC-L pipe ends decontamination: decontamination equipment assembly / hot leg*

koncev sistema reaktorskega hladiva in doseči lokalno čistočo notranjosti cevi. Postopek se doseže v dveh korakih: z uporabo peskanja z elektrokorundom, ki odstrani oksidne obloge in nato pršenja s steklenimi delčki, da bi zmanjšali površinsko napetost in zgladili površino; z uporabo zaprtega sistema s podtlakom, kar prepreči uhajanje abrazivnih delcev in prahu v ozračje (prepreči se razvitje aerosolov) in zagotovi najmanjšo količino nastalih radioaktivnih odpadkov.

1.2.4 Varjenje

Varjenje na cevovodih sistema reaktorskega hladiva bo potekalo s postopkom argonskega varjenja.

Konci priključkov uparjalnika in sedanja kolena bodo strojno obdelani na posebno geometrijsko obliko za varjenje v ozkem žlebu, kakor je prikazano na sliki 4.

Zvari na spojih bodo narejeni z daljinsko upravljano napravo. Izdelani bodo v večslojni tehniki in z nespremenljivimi parametri varjenja po obodu zvara. V primeru razlik v zunanjem premeru se končni nanos izvede avtomatsko ali ročno, odvisno od velikosti odstopanj.

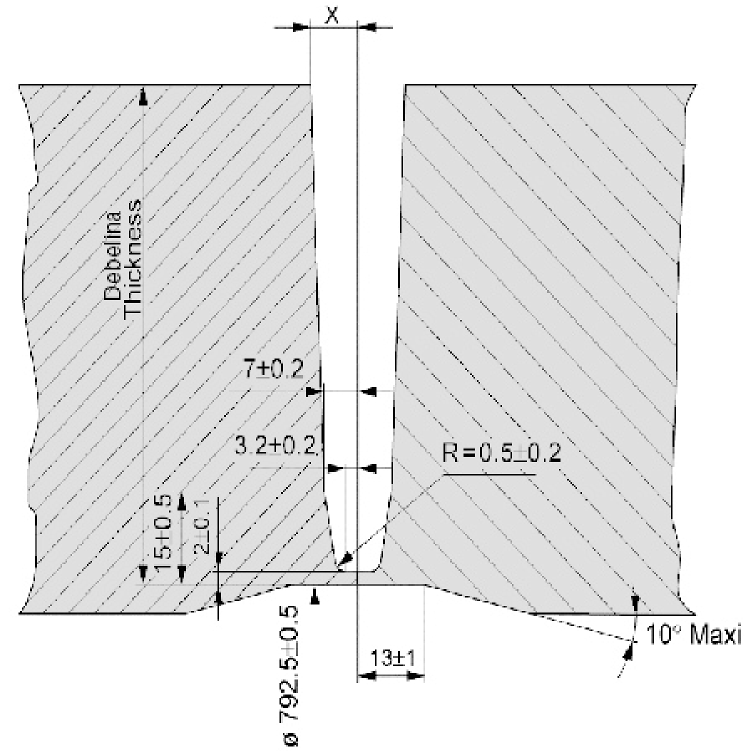
the reactor coolant pipe ends, and to achieve local cleanliness of pipe interiors . This process is performed in two steps. First, blasting by electrocorundum to remove the oxide layer, followed by blasting with glass beads to improve the superficial stress conditions and to smooth the surface. Use of a closed-circuit system with sub-atmospheric pressure prevents abrasive particles and dust from escaping into the atmosphere (aerosol build-up is avoided) keeping radioactive waste build-up to a minimum.

1.2.4 Welding

The welds in the RCS piping system will be performed with the mechanized GTAW process.

The SG nozzle ends and the existing elbows will be machined to a specific narrow-gap weld geometry as shown in Figure 4.

The weld joints will be made using a remote-controlled narrow-gap orbital welding unit. The welds will be performed using a layer-by-layer technique and with constant welding parameters around the weld circumference. In case of differences in outside diameter, overlay welding could be carried out either automatically or manually, depending on the height of the weld builtup.



debelina thickness	64 to 65.9	66 to 67.9	68 to 69.9	70 to 71.9	72 to 73.9	74 to 75.9	76 to 77.9	78 to 79.9	80 to 81.9	82 to 83.9
X (+0.3; -0.3)	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10	10.1	10.2

Sl. 4. *Priprava zvarnega roba*
Fig.4. *Weld edge preparation*

Zaradi velike kakovosti zvarov, ki so posledica optimalne tehnike varjenja in ponovljivosti postopka, je možnost napake zelo majhna. Vseeno pa bo pripravljen tudi popravni postopek varjenja. Glede na naravo napake bo omogočen daljinski postopek strojne obdelave za argonsko varjenje ali ročni postopek varjenja.

Na koncu bodo zvari (zunaj cevi) zbrušeni. Na celotnem zvaru se bodo izvedli naslednji neporušni preskusi:
– test s tekočimi penetranti,
– rentgenski test,
– ultrazvočna preskušanja.

1.3 Sekundarni in pomožni cevovodi, instrumentacija in nadzor ter spremembe, povezane s povečanjem moči

Med zamenjavo uparjalnika bo veliko dejavnosti potekalo na sekundarnih sistemih. Predstavljamo najpomembnejše:

Sistem glavne pare

Odstranitev dela cevi in kolena glavnega parnega voda je potrebna zaradi odstranitve starega uparjalnika in ponovna vgradnja po namestitvi novega uparjalnika.

Sistem glavne napajalne vode

- Preusmeritev cevovoda glavne napajalne vode zaradi priključitve na priključek novega uparjalnika (nova lokacija),
– odstranitev in ponovna namestitev instrumentacijskih cevi (zaradi proste poti in lokacij novih instrumentacijskih priključkov),
– odstranitev obvoda predgrelnika, grelnih cevovodov in priključene instrumentacije (nova uparjalnika nimata predgrelnika),
– zamenjava rotorja črpalke napajalne vode in vgradnja novih notranjih delov v regulacijske ventile napajalne vode, ki se jim poveča gib (večji pretoki in zato povečani padci tlaka, povezani s povečanjem moči, zahtevajo večji pretok črpalke in večjo zmogljivost regulacijskih ventilov),
- omogočeno delovanje s tremi črpalkami napajalne vode.

Sistem za kaluženje uparjalnikov

- Odstranitev sedanjih cevi za kaluženje znotraj prostora za uparjalnik,
– vgradnja spremenjenih cevi za kaluženje v prostoru za uparjalnik, ki bodo uravnavale pretok iz dveh priključkov novega uparjalnika in omogočile 5-odstotni imenski pretok napajalne

Due to the high quality of welds resulting from the optimized welding technique and the reproducibility of the mechanized process, the risk of defects is very low. However, repair welding procedures will also be prepared. Depending on the nature of the defects involved, either the mechanized remote-controlled GTAW process or a manual welding process will be used.

The welds will be ground (outside the pipe) after completion. The following non-destructive examination (NDE) will be performed on the entire completed weld:
– liquid penetrant test,
– X-ray,
– pre-service inspection ultrasonic test .

1.3 Secondary and auxiliary piping, instrumentation and control, uprating related modifications

During the SGR, a lot of activities are performed on the secondary systems. The main ones are described below.

Main steam system

Removal, for clearance purposes, of a section of main steam pipe for removal of existing steam generator and reinstallation, once new steam generator is installed.

Main feedwater system

– Re-routing of the feedwater pipe to attach to the replacement steam-generator nozzle (new location),
– removal and reinstallation of the steam generator instrumentation pipe and tubing (clearance purposes and new instrument tap locations),
– removal of the preheater bypass and warm-up piping and associated I&C (no preheater bypass required for the replacement steam generator),
– replacement of the feedwater pump impellers and installation of new trim in the feedwater control valves with increased stem travel (higher feedwater flows and resulting increased pressure drops associated with the uprating require increased pump performance and control valve capacity),
- enable operation with 3 FW pumps.

Blowdown system

- Dismantling of the existing blowdown (BD) pipes inside the steam generator cubicle,
- installation of a revised blowdown piping in the steam generator compartment to balance the flow from the two blowdown connections provided on the replacement steam generator and to get a flow

vode v novem cevovodu pri spoju s sedanjim cevovodom (mogoče poznejše spremembe sistema za kaluženje za večji pretok brez posegov v prostoru za uparjalnik),
– vgradnja odzračevalnih priključkov na visokih točkah cevovoda za kaluženje in priključka kondenzatnega sistema za polnjenje sistema za kaluženje, da se prepreči vodni udar pri ponovnih zagonih sistema.

Sistem pomožne napajalne vode

- Odstranitev dela cevovoda in kolena pomožne napajalne vode zaradi odstranitve starega uparjalnika in ponovna vgradnja po namestitvi novega uparjalnika,
– zamenjava notranjih delov regulacijskih ventilov pomožne napajalne vode, da bi omogočili dodatno rezervo za obratovanje črpalk pomožne napajalne vode.

Sistem drenaže grelnikov

– zamenjava cevi drenaže grelnikov št. 2 iz 12" na 24" (sedanja velikost cevi je komaj zadostna za zahtevani samoodzračevalni pretok).

Kondenzatni sistem

– Zamenjava sesalne cevi kondenzatnih črpalk iz 24" na 30", da bi se zmanjšal padec tlaka ob povečanih pretokih,
– delovanje s tremi kondenzatnimi črpalkami, da bi omogočili ustrezen tlak in prilagodljivost ob povečanih pretokih.

1.4 Večnamenska stavba

V sklop projekta zamenjave uparjalnikov je vključena tudi večnamenska stavba, prikazana v tlorisu na sliki 5, ki je namenjena za:
– shranjevanje starih uparjalnikov,
– shranjevanje nizko- in srednjeradioaktivnih odpadkov, ki nastanejo pri zamenjavi,
– prostor za dekontaminacijo,
– prostor za urjenje,
– prostor za osebje radiološke zaščite.

Objekt je dovolj močan, da se ne bi porušil ob hipotetičnem potresu varne zaustavitve elektrarne. Izvedba objekta tudi zagotavlja, da nivo sevanja ob ograji, predpisan v lokacijskem dovoljenju, v nobenem primeru ne bo presežen.

Projekt je bil izdelan v skladu s slovenskim zakonom o graditvi objektov; zato je bil predložen PGD (projekt za pridobitev gradbenega dovoljenja) ter podprt z ustreznim projektom za izvedbo – PZI.

Za pridobitev dovoljenj je bil PGD osnova v

equal to 5% of nominal feedwater flow in the new piping at the connection with the existing piping (possible later modifications of BD system for higher flow, without any works in the cubicles),
– installation of vents at high points in the blowdown piping and provision of a connection to fill the blowdown system from the condensate system in order to prevent the water-hammer effect when restarting the system.

Auxiliary feedwater system

– Removal, for clearance purposes, of a section of auxiliary feedwater pipe for removal of existing steam generator and reinstallation once the new steam generator is installed,
– replacement of the auxiliary feedwater-control valve trims to provide additional margin for AF pump operation.

Heater drain system

– Replacement of the number 2 heater drain pipe, increasing the size from 12" to 24" (the existing pipe size is marginal for the required self-venting flow).

Condensate system

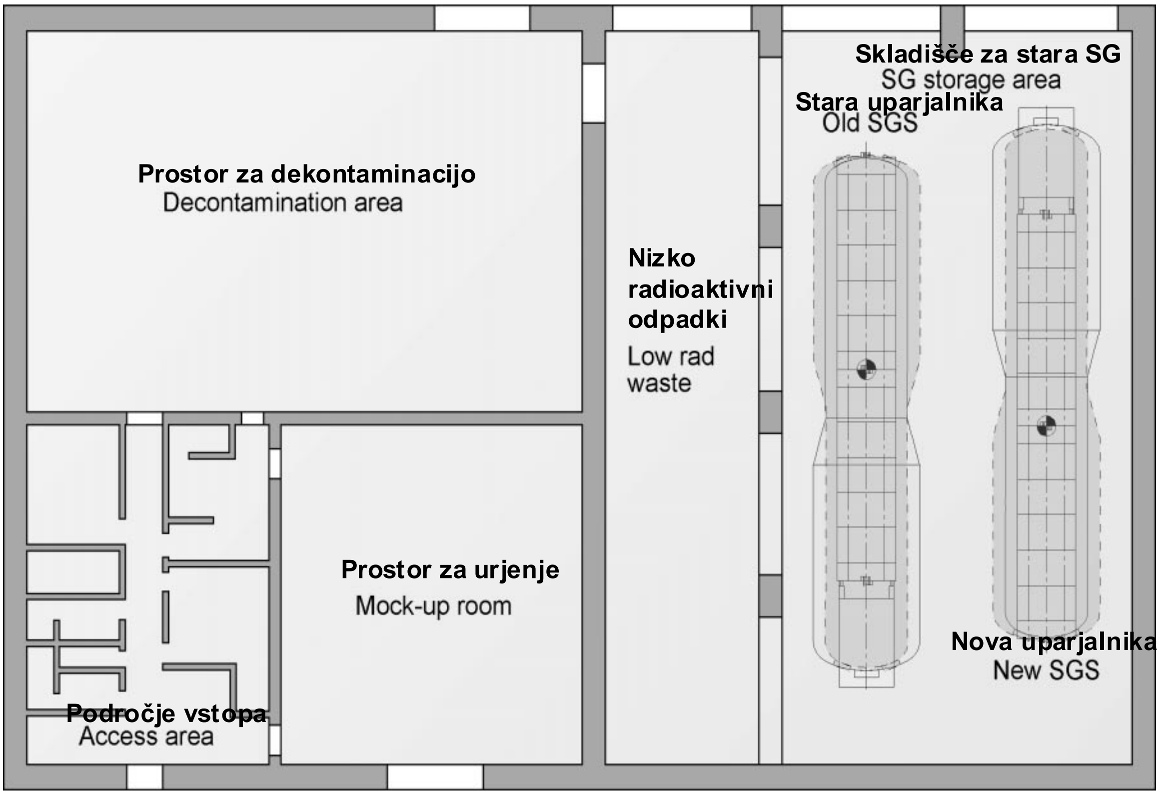
– Replacement of the condensate pump suction pipe, increasing the size from 24" to 30" in order to reduce pressure drop at uprate flows,
– operation with three CY pumps to provide adequate pressure and flexibility at uprate flows.

1.4 Multi-purpose building

Within the scope of activities for the steam generator replacement, a multi-purpose building with the layout shown in figure 5 has also been included for the following purposes:
– storage of old steam generators,
– storage of low and intermediate-level waste from the SG replacement,
– decontamination area,
– mock-up and training area,
– personnel radiation-health area.

The facility has been designed as a non-safety related building but calculated for non-collapse in the case of an SSE. Furthermore the radiation level at the site fence established in the site permit shall not be surpassed.

The design was performed according to the Slovenian construction regulations, for which purpose a design for construction permit (PGD) was granted, supported later on for construction purposes with the corresponding design for construction performance (PZI) documents.



Sl. 5. *Večnamenska stavba*
Fig.5. *Multi-purpose building*

skladu z običajnim gradbenim dovoljenjem ter oceno jedrskih vidikov.

Stavba je opremljena s sistemom HVAC, ki vključuje filter HEPA, da bi preprečeval uhajanje radioaktivnosti in znotraj stavbe vzdrževal podtlak ter primerne okoliščine za osebje. Prostor za dekontaminacijo se bo uporabljal za dekontaminacijo, v njem bo 5-tonsko dvigalo, povezano s sistemom demineralizirane vode in neodvisnim sistemom stisnjenega zraka. Monitorji sevanja z lokalnimi alarmi bodo vgrajeni v prostorih za shranjevanje in dekontaminacijo in povezani z glavno kontrolno sobo elektrarne. Stavba je bila uporabljena tudi kot prostor za shranjevanje novih uparjalnikov med zimo 1999-2000. Nova uparjalnika sta bila v elektrarno pripeljana v septembru 1999.

2 DOKUMENTACIJA ZA PROJEKT IN PRIDOBITEV DOVOLJENJ

V pripravljalni fazi projekta je treba pripraviti veliko dokumentov. Pripraviti je treba naslednje glavne kategorije dokumentov:

– dokumentacijske pakete za trajne in začasne spremembe. Poleg projekta in projektnih izračunov vsebujejo varnostno presojo in varnostno oceno. Ti paketi so podlaga za proces pridobivanja dovoljenj. Ko vse te dokumente natančno pregleda JEK (SSP – Strokovni svet pogona in VS –

For the licensing, the PGD was the basis according to the normal construction license which joined an assessment with regard to the nuclear application, having received the construction permit in this way.

The whole building is equipped with a nuclear HVAC system comprising a HEPA filter to avoid the emission of radioactivity and to maintain a sub-pressure inside the building, as well as for personnel comfort. The decontamination area will be used for decontamination activities and is also equipped with a 5 ton crane. It also has a connection to the de-mineralized water system and an independent compressed air system. Radiation monitors with local alarms are connected to the control room and installed in the storage and decontamination rooms. The building has also served as a storage place for the new steam generators during the winter 1999 / 2000. The new steam generators arrived on site in September 1999.

2 DOCUMENTATION FOR ENGINEERING AND LICENSING

During the preparatory/engineering phase of the project, numerous documents have to be prepared. The following main categories of documents are to be prepared:

– document packages for permanent and temporary modifications. Besides all the design and design calculation aspects these documents include the safety evaluation screening and safety evaluation. These packages are the basis of the licensing process. After a detailed review of these documents by NEK (by

Varnostni svet), jih pošlje na Upravo RS za jedrsko varnost. Metodologija za pridobitev dovoljenj je v skladu z zahtevami Zvezne jedrske upravne komisije ZDA (10CFR50.59),
– dokumentacijo za kvalifikacijo posebnih postopkov, opreme in osebja,
– dokumentacija za nakup začasne in trajne opreme,
– dokumentacijske pakete za vgradnjo,
– dokumentacijo izvedenih del.

Upoštevati je potrebno tudi ustrezno slovensko zakonodajo.

KOC-Krško Operating Committee and KSC-Krško Safety Committee) these documents will be forwarded to the Slovenian Nuclear Regulatory Body (URSJV). The methodology for licensing is in accordance with the US NRC (10CFR50.59),
– documents for the qualification of special processes, equipment and personnel,
– documents for the procurement of temporary and permanent equipment,
– document packages for site implementation (installation packages),
– as-built documentation.

Applicable Slovenian legislation shall also be respected.

3 ORGANIZACIJA IN ČASOVNI NAČRT PROJEKTA

Projektno skupino konzorcija sestavljata podjetje Siemens v Erlangnu v Nemčiji in Framatome v Chalonu v Franciji. Tudi JEK ima zelo dobro projektno organizacijo, da bi se lahko odzvala na vse zahteve projekta. Zaradi neposrednega stika ima Konzorcij svojega zastopnika v elektrarni med celotno dobo zamenjave. Le-ta je vključen tudi v poslovanje s slovenskimi podjetji.

Zaustavitev elektrarne zaradi zamenjave uparjalnikov se prične 15. aprila 2000; zamenjava naj bi po načrtu trajala 28 dni, celoten remont pa približno dva meseca.

3 PROJECT ORGANIZATION AND SCHEDULE

The Consortium project team includes Siemens located in Erlangen, Germany and Framatome located in Chalon, France. Krško NPP also has a very good project organization in order to be able to react to the requirements of the project. For interface purposes the Consortium has a representative on site during the whole engineering phase, who is also involved in dealing with Slovenian companies.

The shut down for the steam generator replacement starts on April 15, 2000. The replacement window is scheduled for a period of 28 days, and the entire outage for approximately two months.

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Nove smernice za simuliranje dinamičnih odzivov stavbe

Uvodna beseda

Novembra 1999 je izšel »prototip« smernic **VDI 6020** - Zahteve za postopke izračunov simuliranja stavb in naprav, ki obravnavajo simuliranje dinamičnih odzivov stavbe na spremembe zunanjih parametrov ali želenih vrednosti pri krmiljenju notranje temperature.

Najprej si oglejmo, zakaj je takšno priporočilo potrebno po mnenju oddelka družbe VDI – oddelka za tehnično opremo stavb. V zadnjih 20 letih se po eni strani bistveno povečuje število klimatiziranih stavb, hkrati pa se povečuje skrb za racionalno rabo energije na vseh nivojih in tudi pozornost do naravnega okolja, ki ni več samo politično geslo za lovljenje neukih volivcev. Ker je že dolgo znano, da je pri vzdrževanju ugodja v stavbah najlaže in najceneje prihraniti energijo, ki je ni treba vložiti v obratovanje, da se doseže enak ali še vedno ustrezen učinek, se proizvajalci opreme in projektanti že nekaj časa ozirajo po načinih za optimizacijo grelnih, predvsem pa hladilnih in klimatizacijskih sistemov.

Razlogi za nastanek smernic

Varčevanje pri stroških obratovanja in investicije se seveda začne že v glavah investitorjev in projektantov. Zasnove pa so v standardni obliki še vedno razmeroma potratne, deloma zaradi metod izračunov, deloma zaradi še vedno opazne miselnosti, da mora naprava ponuditi postavljene parametre tudi v redkih ekstremnih razmerah, zraven pa sodi še primerna »rezerva za mirno spanje«. Taka zasnova pomeni nepotrebno veliko napravo, prevelik pretok zraka, povečano število dovodnih difuzorjev in odvodnih rešetk, pa tudi zračnih kanalov. To vodi v povečanje investicijskih stroškov pri nakupu naprav in izvedbi napeljave, večji zakup električne energije, povečanje jalove moči, pa tudi zmanjšano udobje zaradi nepotrebnega prepiha.

Nemške smernice za izračunavanje hladilnih bremen VDI 2078 so v Evropi še vedno osnova za sestavljanje računalniških programov. Prve konkretne pobude za optimizacijo so prišle od proizvajalcev opreme, ki so v konkurenčnem boju za tržišče morali s čim manjšimi stroški dosegati pogodbene vrednosti. Prvi profesionalni računalniški programi, ki so omogočili približevanje k optimalni izbiri naprave, so bili prav tovarniški, tu pa so prednjačili Američani.

Novodobno načelo hišne tehnike je: **V POSLOPJU NAJ BO LE TOLIKO TEHNIČNIH NAPRAV, KOLIKOR JE NEOBHODNO POTREBNO. TA TEHNIKA NAJ BO VARČNA IN PRIJETNA ZA OKOLJE**. Tako naj bo najprej doseženo spoznanje, da se lahko razmere v prostorih v ekstremnih okoliščinah gibljejo tudi zunaj idealnih meja. Pri tem je treba upoštevati kot zalogo za kratke preobremenitve tudi akumulacijsko zmožnost objekta.

Te zahteve pomenijo bolj natančne izračune in izbiro naprav, zato pa je treba imeti na voljo potek izračuna, ki omogoča primerjalno presojo različnih gradbenih rešitev in tehničnih ukrepov. Vse naprave v nekem objektu medsebojno vplivajo, gradbene značilnosti in namen objekta pa je prav tako pomemben za celotno obnašanje objekta. Za sodobno projektiranje je treba zajeti vse okoliščine, zato pa uporabimo simuliranje, ki upošteva vse parametre, da se doseže zadostno natančnost.

Tržišče je vse bolj založeno s profesionalnimi računalniškimi programi za izračun in simuliranje toplotnih karakteristik stavbe, ki so bolj ali manj zapleteni po sestavi in uporabi. Kakor je bilo pričakovati, so vsi ti programi med seboj zelo različni, zato pri sicer zadovoljivo kakovostnih izdelkih zaradi različnih upoštevanih robnih pogojev prihaja do različnih rezultatov. Poleg tega se je zgodilo, da so bili uporabljeni računski postopki, ki so bili za ta namen neprimerni in so fizikalne povezave prikazali le delno, nezadostno ali celo napačno.

Poseben problem pri uporabi toplotno energetskih simuliranj stavb in naprav je bil tudi nezmožnost uporabnika, da preveri simulirne rezultate. To pomeni, da je projektant porok investitorju za svoje izračune, ne da bi imel možnost preveriti rezultate.

Zasnova smernic

Nove smernice VDI 6020 so zastavljene v dveh delih, od katerih je izšel prvi:

- list 1 Simuliranje stavb
- list 2 Simuliranje naprav

pri čemer je simuliranje stavb seveda prvi pogoj za simuliranje naprav.

Vsebina je razdeljena na sedem glavnih poglavij:

1. Področje veljavnosti
2. Pripadajoče norme in navodila
3. Razlaga, definicije, formule

4. Uporaba meteoroloških podatkov
5. Osnove za izračune in izvedba
6. Stavbe
7. Testni primeri

Smernice so še v pripravi, zato je razpisan rok do konca maja 2000, ko še sprejemajo pripombe na predlog, in sicer na naslov:
VDI Gesellschaft Technische Gebäudeausrüstung
Postfach 10 11 39
40 002 Düsseldorf

Smernice VDI 6020 imajo namen vnesti nekaj reda med simulirne programe, ki naj bodo sposobni korektnih izračunov po dogovorjenih kriterijih.

Komisija za smernice VDI 6020 v obširni sestavi sedmih diplomiranih inženirjev, enega doktorja inženirja in štirih profesorjev z doktorsko inženirsko izobrazbo je zastavila minimalne zahteve za termične in energetske izračune. Tako je za osnovo poenotila številne robne pogoje in ocenjevalne kriterije in s tem omogočila, če že ne popolno, pa vsaj temeljno preverjanje upoštevanih izkustvenih podatkov. Pri pripravi so namenoma izbrali celo vrsto posebnih primerov, ki omogočajo preverjanje osnovnih algoritmov računskega postopka, ki je sestavni del programov. S tem naj bi med drugim omogočili izdelovalcem programov, da vstavijo robne pogoje, ki so potrebni za testne izračune. Z njimi lahko uporabnik izpelje tudi poljubne druge teste. Že med izdelavo VDI 6020 so različni izdelovalci programov upoštevali nujnost te zahteve in omogočili v svojih izdelkih vnos želenih podatkov.

Poleg tega je v smernicah nakazan postopek, s katerim je bil preverjen testni primer in s katerim lahko tudi uporabnik simulirnega postopka ali izdelovalec programa preveri tudi druge primere.

Področje uporabe

Smernice dopuščajo uporabniku načelno preskušanje računskih postopkov, ki so uporabljeni v programih za termično in energijsko simuliranje stavb. To se doseže s preračunavanjem testnih primerov z določenim simulirnim programom in s primerjavo rezultatov s tistimi iz VDI 6020.

Smernice dajejo navodila, kako se lahko izvedejo testiranja poljubnih drugih primerov.

Podane so minimalne zahteve glede na VDI 6020, ki jih mora uporabiti izdelovalec programa za računski postopek kar se tiče algoritmov in parametrov. Komisija je testirala metode izračunov neustaljenih odzivov prostora z več programi, priporoča pa le tiste, ki so v smernicah opisane metode v programu pravilno uporabili.

Za testne primere je komisija uporabila naslednje simulirne programe:

DOE – 2	verzija 2.1 E
DS-THERM	verzija 3.26
GEBSIMU	verzija 4.32
TAS	verzija 8.0
TRN SYS	verzija 14.2 Update 12/98

Posebnosti glede na doslej uveljavljene postopke

Za računske podatke glede vremenskih razmer, smeri vetra, hitrosti vetra, temperature zraka, oblačnosti, padavin, zračnega tlaka, relativne vlažnosti, neposrednega sončnega sevanja, difuznega sevanja, osvetljenosti, dolgovalovnega sevanja in atmosferskega odboja sevanja so podane zahteve oziroma postopki in način priprave statističnih podatkov za potek celotnega leta v urnih razmikih. Uporabljeno je preskusno referenčno leto (PRL - TRY), ki predstavlja potek standardnega leta in ne povprečkov posameznih dni iz več let, pri tem pa se povprečja daljših časovnih obdobij (meseca, ogrevalne sezone, poletne sezone) ujemajo z dolgoletnimi povprečji. Podatki so izdelani za 14 regij v Nemčiji.

V Sloveniji takih preciznih in obdelanih podatkov nimamo. Za take primere, ki jih imajo tudi v Nemčiji (nove zvezne dežele po združitvi), pa dopuščajo v prehodnem času do izdelave PRL za nove pokrajine uporabo podatkov po sistemu podobnosti z že obdelano regijo, če ni primerljiva, pa predlagajo uporabo podatkov, ki so na voljo za vso Evropo kot kratko referenčno leto (KRL - SRY).

Povezava s standardi in smernicami

Standardi:

DIN 4108	Toplotna zaščita v visoki gradnji
DIN 4701-1	Pravilnik za izračun porabe toplote v poslopjih; osnove izračunov
DIN 4701-2	Tabele, slike , algoritmi
DIN 4710	Meteorološki podatki za izračun porabe energije grelnih in prezračevalnih naprav
DIN 5034	Dnevna svetloba v notranjih prostorih
DIN EN 410	Steklo v gradbeništvu; določanje svetlobno tehničnih in sevalno fizikalnih veličin za zasteklitve
DIN EN 13786	Toplotne značilnosti gradbenih elementov, dinamično termične lastnosti; postopek izračuna

Smernice:

VDI 2078	Izračun hladilnega bremena klimatiziranih zgradb
VDI 2067 list 11	Gospodarnost tehničnih naprav v zgradbah; postopek izračuna porabe energije ogrevanih in klimatiziranih zgradb
VDI 3804	Prezračevalne naprave za prezračevalne naprave
VDI 6021	Izmenjava podatkov za izračun termičnih obremenitev zgradb
ASR	Državne delovne smernice

Povzetek

Obširne smernice »Zahteve za postopke izračunov simuliranja zgradb in naprav«, kakor se imenuje novi VDI 6020, v uvodnem delu razložijo razloge za njihov nastanek, ki so posledica vse večje skrbi za racionalno izrabo energije in tudi pozornosti do okolja.

V nadaljevanju navaja uporabljene standarde in smernice, ki zaokrožujejo stare uveljavljene predpise z novo nastajajočimi in se povezujejo že v evropsko zakonodajo.

V poglavju pojasnila, definicije in formule najprej razlagajo uporabljene pojme in osnovne formule, ki so potrebne za popis dogajanja v toplotnem pogledu ob dinamičnih spremembah vhodnih parametrov.

Pod uporabo meteoroloških podatkov predpisujejo vir podatkov – testno referenčno leto, pa tudi pogoje za začetek ogrevalne in klimatizacijske sezone – predlagajo se nova izhodišča.

Osnove za izračune in izvedba predpisujejo metode za reševanje osnovne diferencialne enačbe in ugotavljajo, katere od uveljavljenih metod so primerne, dopuščajo pa tudi drugačne metode, s tem da morajo biti rezultati primerljivi s temi, ki jih dosežemo s predpisano metodologijo.

Poglavje zgradbe obravnava termični model poslopja ter vse vplivne dejavnike in robne pogoje, ki jih je obvezno upoštevati pri sestavi simulirnega programa.

Testni primeri so obširna podlaga za primerjave katerihkoli drugih programov z obravnavanimi, ki so preverjeni od komisije.

Na koncu smernic so še delovne priloge za izbiro robnih pogojev in meteoroloških podatkov.

Celoto bi bilo težko predstaviti v omejenem obsegu, tako da pričujoči zapis služi kot informacija za tiste, ki si nameravajo smernice sami ogledati.

Tomaž Goršič
mag. Dragutin Kelšin

Sejmi in konference
Fairs and Conferences

8. do 11. maj 2000: **“Mednarodne oznake varjenja” (International Welding Codes)**, Amsterdam, Nizozemska – informacije: Oudezijds Voorburgwal 316A, 1012 GM Amsterdam, Nizozemska; tel.: +31 20 638-28-06; faks: +31 20 620 21 36; http://www.cfpa.com

22. do 24. maj 2000: **“Akumulatorski sistemi in tehnologije” (Battery Systems and Technologies)**, Amsterdam, Nizozemska – informacije: Oudezijds Voorburgwal 316A, 1012 GM Amsterdam, Nizozemska; tel.: +31 20 638-28-06; faks: +31 20 620 21 36; http://www.cfpa.com

9. do 14. september 2000: **“Hipoteze IV – Energija vodika” (Hypothesis IV – Hydrogen Power)**, Stralsund, Nemčija – informacije: Fachhochchule Stralsund, University of Applied Sciences, Department of Electrical Engineering and Computer Science, Zur Schwedenschanze 15, 18435 Stralsund, Nemčija; tel.: +49 3831 456-811, 456-703; faks: +49 3831 456-687; e-mail: hypothesis@fh-stralsund.de; http://www.hypothesis.de

28. in 29. september 2000: **“Slovenski kemijski dnevi 2000”**, Maribor – informacije: FKKT, SKD’2000, Smetanova 17, 2000 Maribor; tel.: (062) 229-44-00; faks: (062) 227-774; e-mail: skd@uni-mb.si; http://atom.uni-mb.si, http//www.chem-soc.si

22. do 25. oktober 2000: **“Trajna gradnja 2000” (Sustainable Building 2000)**, Maastricht, Nizozemska – informacije: Conference Secretariat SB 2000, P.O.Box 1558, 6501 BN Nijmegen, Nizozemska; tel.: +31 24 323-44-71; faks: +31 24 360-11-59; e-mail: sb2000@novem.nl; http://www.novem.nl/SB2000

25. do 27. oktober 2000: **“Energija in okolje 2000” (Energy and the Environment 2000)**,Opatija, Hrvaška – informacije: Croatian Solar Ebergy Association, Vukovarska 58, HR-51000 Rijeka, Hrvaška; tel.: +385 51 67-15-06; faks: +385 51 67-58-01; e-mail: huse@rijeka.riteh.hr; http://www.riteh.hr/ee2000

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Professional Literature

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Professional Literature

Ocene knjig

M. Bargende – J. Wiedemann: Kraftfahrwessen und Verbrennungsmotoren
3. Stuttgarter Symposium

Zal.: Expert Verlag, Renningen – Malmsheim 1999.
Obseg: format 14,5 x 21 cm, 916 strani, 720 slik, 38 preglednic.
Cena je 184 DEM.

Optimiranje posameznih parametrov vozila zahteva pospešene raziskave in tehnične izboljšave na področju vozil in motorjev z notranjim zgorevanjem. Težišče raziskav je bilo v preteklem obdobju in bo tudi v prihodnje usmerjeno predvsem k ugodnejši porabi goriva, znižanju deleža emisije škodljivih komponent v izpušnih plinih, hrupa in voznih uporov ter povečanju gospodarnosti, varnosti in udobnosti pri vožnji vozil.

V knjigi so predstavljena predavanja s 3. stuttgartskega simpozija o vozilih in motorjih. Vsebine podajajo pregled rezultatov na področju raziskav v nemški avtomobilski industriji. Podane pa so tudi smernice in obeti za prihodnost.

Vsebina knjige je razdeljena na poglavja o razvoju motorjev in vozil ter razvojnih in preskusnih tehnologijah vozil.

Prvo poglavje obravnava sisteme neposrednega vbrizgavanja pri ottovih in dizelskih motorjih, zunanjo in notranjo pripravo delovne zmesi v valju motorja, procese zgorevanja in dogorevanja produktov zgorevanja v sistemu katalizatorjev, metode preskušanja in tridimenzionalna simuliranja predvsem na področju procesov zgorevanja ter razvoj posameznih sestavnih elementov motorja.

V drugem poglavju so podane raziskave na vozilih, ki so povezane predvsem s področjem vozne in aeroakustike, udobnost vožnje potnikov, vozne in aerodinamike ter tehnologijo preskušanja zračnega upora v zračnih kanalih.

V zadnjem poglavju se avtorji omejijo predvsem na problematiko tehnike regulacij in avtomatizacije, strategije uporabe vozil in elektronsko podprtih krmilnih funkcij vozila, tehnologijo simuliranja voznih karakteristik vozila v realnem času in programsko opremo, potrebno pri podpori računalniško podprtega razvoja in preskušanja vozil. Na vseh področjih so podani rezultati raziskav, ki so bistveno prispevali k napredku pri razvoju vozil oziroma se z njihovim uvajanjem pričakujejo obetajoče izboljšave.

Knjigo priporočam vsem, ki se pri svojem delu srečujejo z motorji z notranjim zgorevanjem in z vozili na področju razvoja ali uporabe.

I. Prebil

G. Müller – C. Groth: FEM für Praktiker

Zal.: Expert Verlag, Renningen – Malmsheim, 4. dop.izd. 1997.
Obseg: format 16 x 23 cm, 857 strani.
Cena je 148 DEM.

Problemi v vsakdanji tehnični praksi so večinoma tako kompleksni, da se je praktično nemogoče dokopati do analitične rešitve, ali pa bi nam ta pot vzela preveč dragocenega časa. Taki problemi so rešljivi z uporabo numeričnih metod na bolj ali manj zmogljivih računalnikih.

Metoda končnih elementov (MKE) je postala zelo uporabno orodje, tako za inženirsko kakor za znanstveno-raziskovalno prakso. Tržišče ponuja danes kopico, uporabniku bolj ali manj prijaznih programskih paketov, ki slonijo na uporabi metode končnih elementov. Če se odločimo rešiti našo nalogo z enim od programskih paketov, se osredotočimo zgolj na modeliranje problema in vrednotenje rezultatov. Vmesni korak računanja ali procesiranja pa je domena programskega orodja.

Začetnik težko najde odgovore na vprašanja, kateri programski paket je najboljši za njegovo področje dela in katerega izbrati, kako modelirati naš problem in kako pravilno ovrednotiti dobljene rezultate. Za vse, ki ste si prvič zastavili ta štiri vprašanja, ima četrta dopolnjena izdaja knjige »FEM für Praktiker« pravo vsebino. Knjiga daje velik poudarek praktični uporabi MKE in je pisana kot učbenik s številnimi primeri. Priložena je tudi zgoščenka s testnima verzijama programov DesignSpace® in ANSYS®. S slednjim je mogoče praktično rešiti vse primere, opisane v knjigi. Začetnik bo iz vsebine dobil dovolj teoretičnega znanja in z reševanjem opisanih problemov tudi dovolj praktičnih izkušenj o poteku analize MKE za nadaljnje samostojno delo. Knjiga je primerna tudi za tiste, ki že imajo tovrstne izkušnje, saj opisani primeri pokrivajo različna področja uporabe analize MKE (strukturna mehanika, dinamika, analiza električnega in magnetnega polja, termodinamika, metode optimiranja ...).

J. Letonje

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Diplome

DIPLOMIRALI SO

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv univerzitetni diplomirani inženir strojništva:

dne 24. februarja 2000: Primož EGART, Janez FURLAN, Drago GRIL, Gregor KOBE, Marko VUČKOVIĆ;

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Članki morajo vsebovati:
- naslov, povzetek, besedilo članka in podnaslove slik v slovenskem in angleškem jeziku,
- dvojezične preglednice in slike (diagrami, risbe ali fotografije),
- seznam literature in
- podatke o avtorjih.

Strojniški vestnik izhaja od leta 1992 v dveh jezikih, tj. v slovenščini in angleščini, zato je obvezen prevod v angleščino. Obe besedili morata biti strokovno in jezikovno med seboj usklajeni. Članki naj bodo kratki in naj obsegajo približno 8 tipkanih strani. Izjemoma so strokovni članki, na željo avtorja, lahko tudi samo v slovenščini, vsebovati pa morajo angleški povzetek.

Vsebina članka

Članek naj bo napisan v naslednji obliki:
- Naslov, ki primerno opisuje vsebino članka.
- Povzetek, ki naj bo skrajšana oblika članka in naj ne presega 250 besed. Povzetek mora vsebovati osnove, jedro in cilje raziskave, uporabljeno metodologijo dela,povzetek rezulatov in osnovne sklepe.
- Uvod, v katerem naj bo pregled novejšega stanja in zadostne informacije za razumevanje ter pregled rezultatov dela, predstavljenih v članku.
- Teorija.
- Eksperimentalni del, ki naj vsebuje podatke o postavitvi preskusa in metode, uporabljene pri pridobitvi rezultatov.
- Rezultati, ki naj bodo jasno prikazani, po potrebi v obliki slik in preglednic.
- Razprava, v kateri naj bodo prikazane povezave in posplošitve, uporabljene za pridobitev rezultatov. Prikazana naj bo tudi pomembnost rezultatov in primerjava s poprej objavljenimi deli. (Zaradi narave posameznih raziskav so lahko rezultati in razprava, za jasnost in preprostejše bralčevo razumevanje, združeni v eno poglavje.)
- Sklepi, v katerih naj bo prikazan en ali več sklepov, ki izhajajo iz rezultatov in razprave.
- Literatura, ki mora biti v besedilu oštevilčena zaporedno in označena z oglatimi oklepaji [1] ter na koncu članka zbrana v seznamu literature. Vse opombe naj bodo označene z uporabo dvignjene številke[1].

Oblika članka

Besedilo naj bo pisano na listih formata A4, z dvojnim presledkom med vrstami in s 3 cm širokim robom, da je dovolj prostora za popravke lektorjev. Najbolje je, da pripravite besedilo v urejevalnilku Microsoft Word. Če uporabljate kakšen drug urejevalnik besedil, prosimo, da besedilo konvertirate v navadno ASCII (tekstovno) obliko. Hkrati dostavite odtis članka na papirju, vključno z vsemi slikami in preglednicami ter identično kopijo v elektronski obliki.

Prosimo, da ne uporabljate urejevalnika LaTeX, saj program, s katerim pripravljamo Strojniški vestnik, ne uporablja njegovega formata. V urejevalniku LaTeX oblikujte grafe, preglednice in enačbe in jih stiskajte na kakovostnem laserskem tiskalniku, da jih bomo lahko presneli.

Enačbe naj bodo v besedilu postavljene v ločene vrstice in na desnem robu označene s tekočo številko v okroglih oklepajih

Enote in okrajšave

V besedilu, preglednicah in slikah uporabljajte le standardne označbe in okrajšave SI. Simbole fizikalnih veličin v besedilu pišite poševno (kurzivno), (npr. *v, T, n* itn.). Simbole enot, ki sestojijo iz črk, pa pokončno (npr. ms^{-1}, K, min, mm itn.).

Papers submitted for publication should comprise:
- Title, Abstract, Main Body of Text and Figure Captions in Slovene and English,
- Bilingual Tables and Figures (graphs, drawings or photographs),
- List of references and
- Information about the authors.

Since 1992, the Journal of Mechanical Engineering has been published bilingually, in Slovenian and English. The two texts must be compatible both in terms of technical content and language. Papers should be as short as possible and should on average comprise 8 typed pages. In exceptional cases, at the request of the authors, speciality papers may be written only in Slovene, but must include an English abstract.

The format of the paper

The paper should be written in the following format:
- A Title, which adequately describes the content of the paper.
- An Abstract, which should be viewed as a miniversion of the paper and should not exceed 250 words. The Abstract should state the principal objectives and the scope of the investigation, the methodology employed, summarize the results and state the principal conclusions.
- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

The layout of the text

Texts should be written in A4 format, with double spacing and margins of 3 cm to provide editors with space to write in their corrections. Microsoft Word for Windows is the preferred format for submission. If you use another word processor, please convert to normal ASCII (text) format. One hard copy, including all figures, tables and illustrations and an identical electronic version of the manuscript must be submitted simultaneously.

Please do not use a LaTeX text editor, since this is not compatible with the publishing procedure of the Journal of Mechanical Engineering. Graphs, tables and equations in LaTeX may be supplied in good quality hard-copy format, so that they can be copied for inclusion in the Journal.

Equations should be on a separate line in the main body of the text and marked on the right-hand side of the page with numbers in round brackets.

Units and abbreviations

Only standard SI symbols and abbreviations should be used in the text, tables and figures. Symbols for physical quantities in the text should be written in Italics (e.g. *v, T, n,* etc.). Symbols for units that consist of letters should be in plain text (e.g. ms^{-1}, K, min, mm, etc.).

Vse okrajšave naj bodo, ko se prvič pojavijo, napisane v celoti, npr. časovno spremenljiva geometrija (ČSG).

All abbreviations should be spelt out in full on first appearance, e.g., variable time geometry (VTG).

Slike

Slike morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot sl. 1, sl. 2 itn. Posnete naj bodo v kateremkoli od razširjenih formatov, npr. BMP, JPG, GIF. Za pripravo diagramov in risb priporočamo CDR format (CorelDraw), saj so slike v njem vektorske in jih lahko pri končni obdelavi preprosto povečujemo ali pomanjšujemo.

Pri označevanju osi v diagramih, kadar je le mogoče, uporabite označbe veličin (npr. *t, v, m* itn.), da ni potrebno dvojezično označevanje. V diagramih z več krivuljami, mora biti vsaka krivulja označena. Pomen oznake mora biti pojasnjen v podnapisu slike.

Vse označbe na slikah morajo biti dvojezične.

Za vse slike po fotografskih posnetkih je treba priložiti izvirne fotografije ali kakovostno narejen posnetek. V izjemnih primerih so lahko slike tudi barvne.

Figures

Figures must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Fig. 1, Fig. 2, etc. Figures may be saved in any common format, e.g. BMP, GIF, JPG. However, the use of CDR format (CorelDraw) is recommended for graphs and line drawings, since vector images can be easily reduced or enlarged during final processing of the paper.

When labelling axes, physical quantities, e.g. *t, v, m,* etc. should be used whenever possible to minimise the need to label the axes in two languages. Multi-curve graphs should have individual curves marked with a symbol, the meaning of the symbol should be explained in the figure caption.

All figure captions must be bilingual.

Good quality black-and-white photographs or scanned images should be supplied for illustrations. In certain circumstances, colour figures may be considered.

Preglednice

Preglednice morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot preglednica 1, preglednica 2 itn. V preglednicah ne uporabljajte izpisanih imen veličin, ampak samo ustrezne simbole, da se izognemo dvojezični podvojitvi imen. K fizikalnim veličinam, npr. *t* (pisano poševno), pripišite enote (pisano pokončno) v novo vrsto brez oklepajev.

Vsi podnaslovi preglednic morajo biti dvojezični.

Tables

Tables must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Table 1, Table 2, etc. The use of names for quantities in tables should be avoided if possible: corresponding symbols are preferred to minimise the need to use both Slovenian and English names. In addition to the physical quantity, e.g. *t* (in Italics), units (normal text), should be added in new line without brackets.

All table captions must be bilingual.

Seznam literature

Vsa literatura mora biti navedena v seznamu na koncu članka v prikazani obliki po vrsti za revije, zbornike in knjige:

[1] Tarng, Y.S., Y.S. Wang (1994) A new adaptive controler for constant turning force. *Int J Adv Manuf Technol* 9(1994) London, pp. 211-216.
[2] Čuš, F., J. Balič (1996) Rationale Gestaltung der organisatorischen Abläufe im Werkzeugwesen. *Proceedings of International Conference on Computer Integration Manufacturing,* Zakopane, 14.-17. maj 1996.
[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

The list of references

References should be collected at the end of the paper in the following styles for journals, proceedings and books, respectively:

[1] Tarng, Y.S., Y.S. Wang (1994) A new adaptive controler for constant turning force. *Int J Adv Manuf Technol* 9(1994) London, pp. 211-216.
[2] Čuš, F., J. Balič (1996) Rationale Gestaltung der organisatorischen Abläufe im Werkzeugwesen. *Proceedings of International Conference on Computer Integration Manufacturing,* Zakopane, 14.-17. maj 1996.
[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

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Članku priložite tudi podatke o avtorjih: imena, nazive, popolne poštne naslove, številke telefona in faksa ter naslove elektronske pošte.

Author information

The following information about the authors should be enclosed with the paper: names, complete postal addresses, telephone and fax numbers and E-mail addresses.

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